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TRANSGRESSIVE-REGRESSIVE CYCLES IN THE IRONSHORE FORMATION, GRAND CAYMAN, BRITISH WEST INDIES

BY

MORAG KATHLEEN COYNE

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

Department of Earth and Atmospheric Sciences

Edmonton, Alberta
Fall 2003

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Dr. W. G. Evans

April 29, 2003

Date Approved

ABSTRACT

Most studies of Caribbean carbonate deposits measure sea level in relation to established highstands. In this study, however, examination of the Ironshore Formation on Grand Cayman revealed a succession of 6 units (A, B, C, D, E, and F) whose deposition ages correlate to transgressive-regressive sea level cycles. The two youngest units, E and F, were discovered during the course of this study. Onshore and offshore fossil dates established that Unit D ranges in age from 123 to 147 ka (average133 ka), Unit E from 95 to 110 ka (average 101 ka), and Unit F from 80 to 87 ka (average 80 ka). Unit D was deposited during the transgression that led to the Sangamon highstand. Units E and F were deposited throughout the transgressive and regressive cycles of substages 5c and 5a, respectively.

From **In Memoriam A. H. H.**
(lines 2561-2568)

There rolls the deep where grew the tree.
O earth, what changes hast thou seen!
There where the long street roars, hath been
The stillness of the central sea.

The hills are shadows, and they flow
From form to form, and nothing stands;
They melt like mist, the solid lands,
Like clouds they shape themselves and go.

--Alfred Lord Tennyson

To Rob MacNaughton and Elizabeth Turner,

who got the whole thing started.

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There had been and is a great group of grad students, post-docs and undergrads wandering in and out of EAS 2-03. My sojourn overlapped with the following: Lisa McKinnon, Jenny Beanish, Alex MacNeil, Rong-Yu Li, Samantha Etherington, Sandy Bonny, Elizabeth Turner, Dustin Rainey, Kelcey Stilwell, Gail Allison, Hilary Corlett and Ray Wheeler. Sam and Liz deserve resounding applause for the help they gave me in the field, particularly when it included wading in chest-high water while (not) avoiding sharp rocks and balancing a knapsack on the head. At NO time did anyone sunbathe on the beach!

The EAS technical, secretarial, and support staff have also been great. To single out a few: Diane Caird ran all of my XRD samples, and trusted me with her *good* mortar and pestle; Don Resultay and Mark Labbe taught me how to use the rock saw, made my thin sections, lent me chisels and extension cords willingly, and were always helpful; Randy Pakan and Mike Fisher more or less patiently showed me how to use computer stuff in the DIF; Doreen Haugen, Judith Enarson and Kathy Saunders were always there to answer my questions.

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CHAPTER 1
OVERVIEW

1.0 INTRODUCTION

The transgressive-regressive sea level and depositional history of the Caribbean over the last 500,000 years corresponds closely to Pleistocene glacial cycles. Several approaches have been used to decipher this history. For example, planktonic and benthic foraminifera in deep sea cores provide a record of ocean $^{18}O/^{16}O$ changes, and consequently ocean temperature and terrestrial ice volume changes, over time (e.g. Shackleton, 1967, 1987; Shackleton and Opdyke, 1973; Imbrie *et al.*, 1984). As part of another approach, the surface and subsurface geology of various Caribbean and Pacific islands and nearby mainlands has been extensively mapped and subjected to a variety of geological dating techniques. On tectonically unstable islands features such as uplifted reef terraces offer testimony of sea level change (e.g. Broecker *et al.*, 1968; Mesolella *et al.*, 1969; Veeh and Chappell, 1970; James *et al.*, 1971; Bloom *et al.*, 1974; Chappell, 1974; Bender *et al.*, 1979; Aharon, 1983; Chappell, 1983; Geister, 1982). On tectonically stable areas features that have been used for this purpose include Bahamian speleothems, caves and solution conduits (Mylroie and Carew, 1988), and paleosol sequences, patch reefs, speleothems and eolianites from Bermuda (Harmon *et al.*, 1978; Harmon *et al.*, 1981; and Hearty and Vacher, 1994).

The Ironshore Formation of Grand Cayman was deposited in response to sea level changes throughout the late Pleistocene, and as such contributes to the body of sea level research established by work on other Caribbean islands. Previous work on Grand

Cayman led to the recognition of four subsurface units in the northeastern part of the island (Vézina, 1997; Vézina *et al.*, 1999). This thesis builds on that record by 1) demonstrating that the formation includes two previously unrecognized younger units, 2) describing and interpreting these units in both their onshore and offshore settings, and 3) comparing and contrasting these successions to analogous sites elsewhere in the Caribbean.

1.1 Geographic and Geological Framework

1.1.1 Location

Grand Cayman is the largest and most westerly of the three Cayman Islands that lie in the northeast Caribbean, ~240 km south of Cuba, 280 km north-northwest of Jamaica and 480 km northeast of Honduras (Fig. 1.1). Little Cayman and Cayman Brac lie 95 km to the northeast. Grand Cayman is 35 km long in an east-west direction, and ranges from 6 km to 14 wide in a north-south direction on the eastern and western parts of the island, respectively. Most of the island is < 3 m above sea level (asl); but heights of 18 m asl are attained near the northern coast on the eastern part of the island (Rigby and Roberts, 1976). There is also a discontinuous ridge that runs roughly east-west along the southeastern part of the island.

1.1.2 Tectonic Setting

Grand Cayman, Cayman Brac, and Little Cayman are situated on the Cayman Ridge (Fig. 1.2). This asymmetrical feature emerges from under extensive sediment in the Yucatan Basin, about 100 km from the base of the British Honduras continental slope,

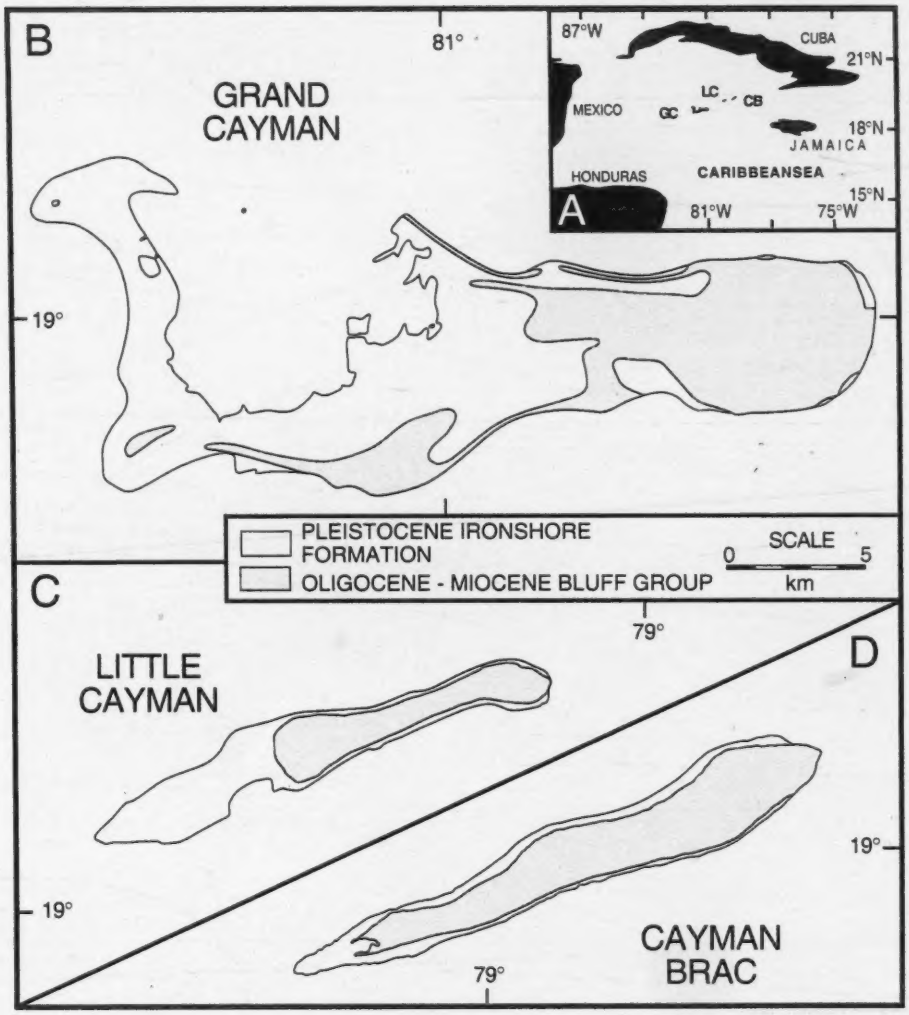

Figure 1.1. A) Location map showing the Cayman Islands, Grand Cayman (GC), Little Cayman (LC), and Cayman Brac (CB). Outcrop maps of B) Grand Cayman, C) Little Cayman, and D) Cayman Brac. (Modified after Matley, 1926; Hunter and Jones, 1989; Jones and Hunter, 1990; Hunter, 1994.)

and extends across the Caribbean Sea to the Sierra Maestra of Cuba (Perfit and Heezen, 1978). The Cayman Trench is found south of and parallel to the ridge. It is a seismically active graben-type trough in the Caribbean Plate that is 120 to 180 km wide, 1600 km long (Perfit and Heezen, 1978), plummets to depths of over 6000 m (MacDonald and Holcombe, 1978; Stoddart, 1980), and consists of at least three segments (Holcombe *et al.*, 1973). The trench is bounded to the north by the Oriente Transform Fault and to the south by the Swan Island Transform Fault. Perfit and Heezen (1978) dredged rocks from the Cayman Ridge and the Cayman Trench and found that the respective samples belonged to completely different assemblages. The trench rocks of the mid-Cayman spreading center are mafic and ultramafic whereas the ridge rocks vary from plutonic and volcanic rocks, to sedimentary and carbonate rocks. The former is typical of major ocean basins, the latter of certain continental margins and island arcs. Shallow-water carbonate rocks were dredged from depths of 1000 m near the reef-producing Rosario and Mysteriosa Banks (Perfit and Heezen, 1978). Below that depth, open ocean sediments were mainly comprised of pelagic oozes. The Eocene-Oligocene shallow-water carbonates presently resting about 3000 m below sea level on both sides of the Cayman Trench allowed Perfit and Heezen (1978) to estimate a subsidence rate of about 6 cm/1000 years in this area. They also postulated that localized uplift after the middle Miocene raised the Cayman Islands. Emery and Milliman (1980) later estimated a subsidence rate of 10 cm/1000 years for the Cayman Trench slope. By contrast, Grand Cayman's Oligocene deposits have a much lower estimated rate of 0.1 to 1.3 cm/1000 years (Emery and Milliman, 1980). These subsidence rates reflect overall subsidence over time, and assume that subsidence was constant.

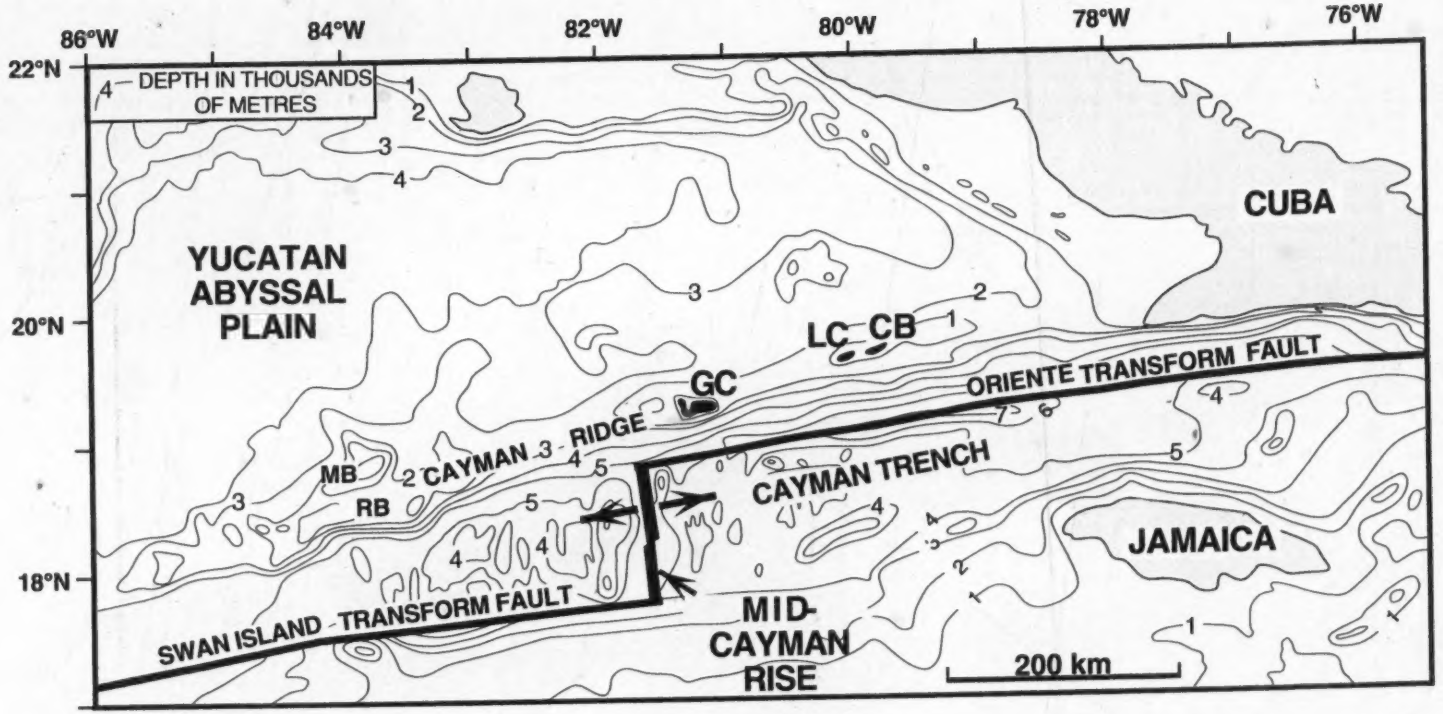

Figure 1.2. Map of the Cayman Trench and its relative position to Grand Cayman (GC), Little Cayman (LC) and Cayman Brac (CB). (MB = Misteriosa Bank, RB = Rosario Bank.) Based on information from Holcombe *et al.* (1973), MacDonald and Holcombe (1978), and Perfit and Heezen (1978). Modified after Pleydell *et al.* (1990),and Hunter (1994).

There are major physiographic differences among the islands, specifically between Cayman Brac and the other two islands. The Brac is noted for the steep cliffs on its east end, which attain heights of more than 40 m. By contrast, both Grand Cayman and Little Cayman are low lying. Cayman Brac's Oligocene bedding dips ~0.5° to the west (Jones *et al.*, 1994a; Jones, 1994), but no regional bedding planes have yet been found on the other islands.

1.2 Island Stratigraphy

1.2. Bluff Group

The Oligocene/Miocene core of each island was originally known as the Bluff Limestone (Matley, 1926), but was renamed the Bluff Formation after researchers discovered it was pervasively dolomitized (Jones and Hunter, 1989). The Bluff Formation was elevated to group status (Jones *et al.*, 1994b) after Jones and Hunter (1989) and Jones *et al.* (1994b) were able to divide the unit into three unconformity-bound successions. These were named, from oldest to youngest, the Brac Formation, Cayman Formation and Pedro Castle Formation (Table 1.1).

The Cayman Formation forms a substantial part of each island. The Pedro Castle Formation has been found on Grand Cayman and Cayman Brac; the Brac Formation comprises the lower part of the cliffs on the east end of Cayman Brac but has not yet been found on the other two islands.

Table 1.1 Formations of the Cayman Islands (modified after Jones, 1994). LC = very common, C = common, LC = locally common, R = rare.

Unit	Age	Lithology	Biota
Ironshore Formation	Pleistocene	Limestone	Corals (VC), Bivalves (VC), Gastropods (C)
Pedro Castle Formation	Pliocene	Dolostone (fabric retentive), dolomitic limestone, limestone	Foraminifera (VC), Corals (C), Bivalves (LC), Gastropods (C), Red algae (C), *Halimeda* (R)
Cayman Formation	M. Miocene	Dolostone (fabric retentive and destructive)	Corals (VC), Bivalves (LC), Rhodolites (LC), Red algae (LC), Foraminifera (LC), Gastropods (R), *Halimeda* (R)
Brac Formation	L. Oligocene	Limestone, or sucrosic dolostone (fabric destructive with pods of limestone)	Bivalves (VC), Foraminifera (VC), Gastropods (C), Red algae (R)

1.2.2 Ironshore Formation

Matley (1926) provided the earliest published descriptions of the Cayman Islands' geology. He borrowed the local term for the hard rocky coastlines (ironshore) when he named the island's youngest formation. Brunt *et al.* (1973) described and broadly divided the Ironshore Formation into reef, backreef, lagoonal, oolitic and shoal "facies". The paleogeographic setting of the Ironshore Formation was discussed by Hunter and Jones (1988; 1990). Studies of the Ironshore Formation biota have included work on bivalves and gastropods (Cerridwen, 1989; Cerridwen and Jones, 1991), coral associations (Hunter, 1994; Hunter and Jones, 1996), conchs (Rehman, 1992; Rehman *et al.*, 1994), and trace fossils (Pemberton and Jones, 1988).

The Ironshore Formation has undergone limited age analysis. Some of the first $^{230}Th/^{234}U$ ages were provided by Emery (1981). However, he considered dates of 155 +/-

10 ka (coral) and 240 +/- 3 ka (a *Strombus* shell) too old. Additional $^{231}Pa/^{235}U$ dating indicated that the uranium concentrations were unusually low, possibly due to uranium loss by weathering, thereby invalidating the $^{230}Th/^{234}U$ results. Woodroffe *et al.* (1983) obtained an average age of 124 +/- 8 ka from four different corals, three of which came from a +2 m "terrace" on Grand Cayman's coast. The fourth was from Cayman Brac.

A paleogeographic model for the Ironshore Formation by Jones and Hunter (1990) suggested that deposition took place when sea level was ~ 6 m above its present level, as indicated by the presence of a wave-cut notch 6 m asl on northeast Grand Cayman. This highstand, evident throughout the Caribbean, is referred to as the Sangamon Highstand (~125 ka). The dates obtained by Woodroffe *et al.* (1983) supported the conclusion that the Ironshore Formation was deposited 125 ka.

The notion that the Ironshore Formation was a single unconformity-bound unit was dispelled when a series of cores were drilled at Rogers Wreck Point, on the northeast coast of Grand Cayman Island (Vézina, 1997). Until that time, attempts to obtain core from the formation had failed because the friable rocks in the formation disintegrated during drilling. The 15 cores used by Vézina (1997) were exceptional for their good recovery, and reached depths ranging from 10 m to 55 m below sea level (bsl). The subsequent recognition of four packages bounded by terra rossa/caliche unconformities led to the naming of Units A, B, C and D. Th/U dating of aragonitic fossil material from each unit showed that they had formed >400 ka<<1,500,000, ~346 ka, ~229 ka, and ~131 ka. Vézina (1997) and Vézina *et al.* (1999) correlated these units to Marine Isotope Stages 11(?), 9, 7, and 5e, respectively. Because the extent of these units was unknown, Vezina *et al.* (1999) refrained from assigning formal stratigraphic names and status. The

units are not defined by facies, but by their unique deposition ages and the unconformities that separate them.

Evidence of possible further divisions in the Ironshore Formation has come from offshore cores obtained from the west coast, and from outcrops on the west part of Grand Cayman. In October 1996, the Port Authority, Cayman Islands Government, drilled four boreholes at proposed cruise ship mooring locations in the George Town harbour. Like the Rogers Wreck cores, these offshore cores exhibited good recovery and strikingly unaltered material. Dr. Brian Jones was allowed access to these cores, and took small samples for further analysis. Dates obtained from the unaltered coral material indicated that at least two sedimentary packages were present, and that the oldest one correlated with Unit D. These unique data, combined with Vézina (1997) and Vézina *et al.*'s (1999) work, led to a re-examination of the Ironshore Formation outcrops on the western Peninsula of Grand Cayman. In November 1999 a hiatus surface previously studied by Jones and Pemberton (1989) was re-examined and traced along the west coast of North Sound. Dates obtained from fossils collected below and above this surface yielded ages with means of ~136 ka, and ~82 ka, respectively. As a result, new units have been recognized in the Ironshore Formation.

1.3 Study Area

Fieldwork was performed at twenty-one different localities where the Ironshore Formation is exposed on the western part of Grand Cayman (Fig. 1.3) (see Appendix A for site names and abbreviations). Five sites at Morgan's Harbour and four at Vista Del

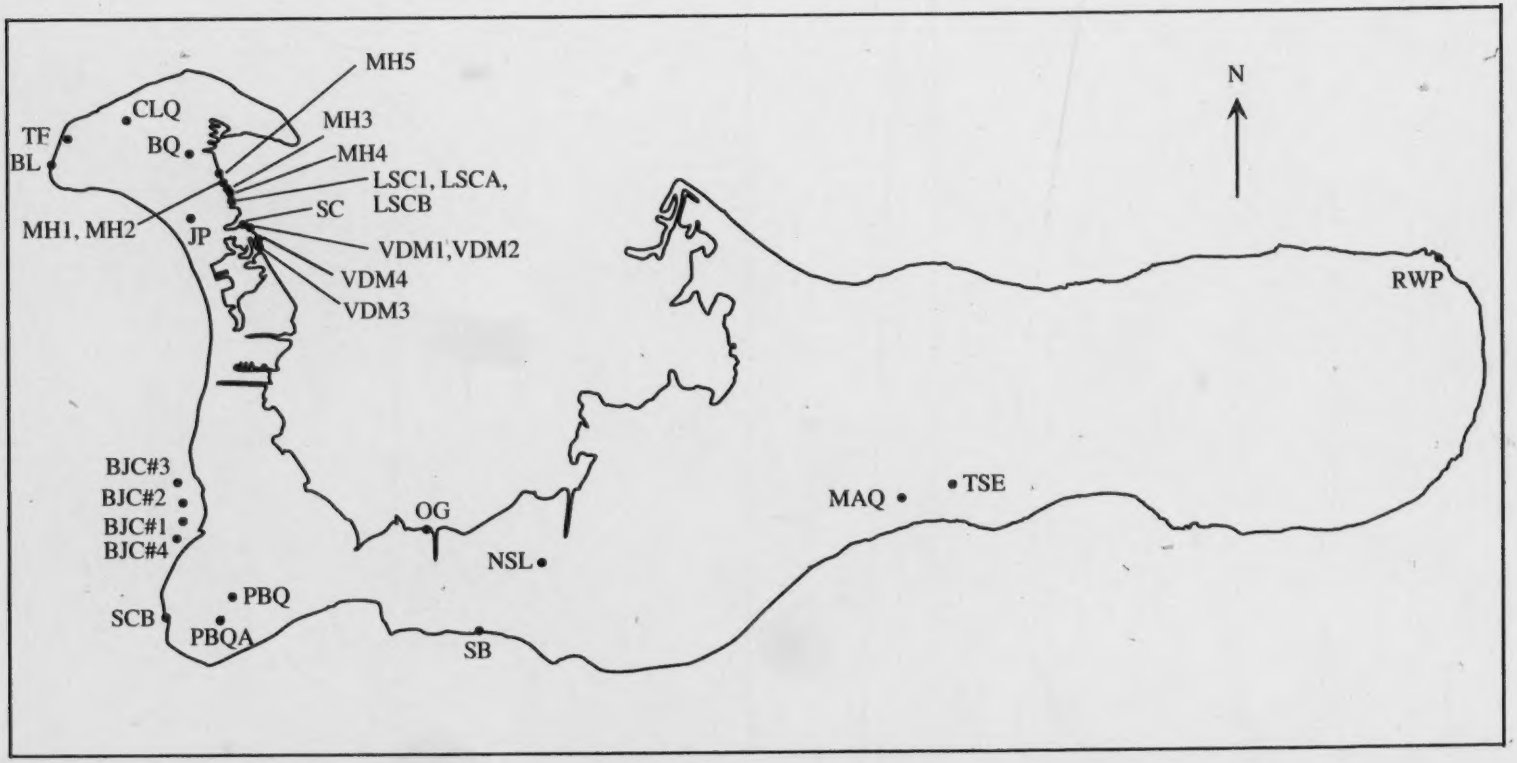

Figure 1.3 Fossil collection sites on Grand Cayman (see Appendix A for site names and abbreviations).

Mar had not previously been studied in detail. Stratigraphic sections were measured and described, and fossil samples (corals, conchs and bivalves) were collected for uranium-series age analysis. Samples were also collected at Omega Gardens, Jackson's Pond, Boat Launch, Tarpon Springs Estate, Canary Lane Quarry, and Spotts Bay for additional analysis. Previously described sections from Smith's Barcadere, Botabano Quarry, Salt Creek, and the Paul Bodden Quarry sites (Jones and Hunter, 1990; Jones, 1994) were re-examined for this study, as well as a section of onshore core, TUF #1. The sections at Botabano Quarry, Salt Creek, and the Paul Bodden Quarries were re-measured and re-sampled.

This study also incorporates four cores that were obtained offshore from George Town harbour, Grand Cayman.

1.4 Objectives

The objectives of this study are to:

1. Describe specific formation outcrops on the western half of Grand Cayman,
2. Date, describe and interpret the successions within the offshore cores,
3. Correlate the onshore and offshore successions found on the western half of Grand Cayman with the successions documented by Vézina (1997) and Vézina *et al.* (1999),
4. Determine past sea level changes (as recorded in the ^{18}O record) from the geological successions in the Ironshore Formation,
5. Refine the paleogeography of Grand Cayman during the deposition cycles of the Ironshore Formation.

1.5 METHODS

1.5.1 Field Work

Field methods used included detailed mapping, measurement, and description of carbonate sedimentary packages and possible hiatus surfaces. Rock and/or fossil samples were collected at each site. Particular attention was paid to specimens that had retained their original aragonite mineralogy because such specimens were needed for Th/U dating. These included branching and head corals (e. g. *Porites* sp., *Montastrea annularis, Diploria* sp., *Acropora palmata, Acropora cervicornis*, and *Madracis* sp.), *Strombus gigas,* and a variety of unidentified bivalves.

1.5.2 Core Analysis

The four offshore cores were initially logged by Brian Jones and Michael Wojcik on Grand Cayman in 1997. Cores BJC#1 and BJC#3 were shipped to the University of Alberta in the summer of 1999; BJC#2 and BJC#4 followed in February 2001. Seven core samples averaging 10 cm long were sent to Core Lab. Can. Ltd. (Calgary, Alberta) for porosity and permeability tests (Appendix B). The rest of the cores were slabbed vertically in half and examined visually. Thin section petrography was used to further analyze the cores' sedimentary, biological, and diagenetic components.

1.5.3 X-Ray Diffraction

The Th/U dating method used for this thesis requires samples to meet a series of set criteria (described in detail in Chapter 2). The primary test of a sample's potential involves X-ray diffraction analysis of each sample to determine the percentage of

carbonate minerals present. Alteration of the fossil's original aragonite to calcite indicates that the fossil has not remained a closed system and cannot be dated via the Th/U system. A calcite percentage above a certain threshold indicates that the specimen will not yield an accurate age.

Specimens were initially examined in hand samples for signs of calcite replacement. If specimens appeared to be unaltered, one sample from each was prepared for X-ray diffraction by removing extraneous sediment prior to grinding the shell or coral into a fine powder with an agate mortar and pestle (3 to 4 minutes). A smear mount on a glass slide was made for each sample: the samples were run on a Rigaku Geigerflex Unit with a fine Cobalt focus tube from $2\theta=25°$ to 40° to include the major aragonite ($2\theta=30.5°$ and 31.8°) and calcite ($2\theta=34.3°$) peaks. Diane Caird (University of Alberta) used Jade 3.0 to calculate peak and area percent.

1.5.4 $^{230}Th/^{234}U$ Radiometric Dating

Radiometric dating techniques employing isotopes from the uranium disequilibrium series have been used extensively to date Pleistocene carbonate sediments (e.g. Osmond *et al.*, 1965; Thurber *et al.*, 1965; Mesolella *et al.*, 1969; Bloom *et al.*, 1974). $^{230}Th/^{234}U$ dating is a ^{230}Th- deficiency method (e.g. reviewed by Gustavsson and Höberg, 1972): ^{234}U decays to its daughter, ^{230}Th, after a certain amount of uranium is incorporated into a sample. The age of the sample can then be calculated using the amounts of both isotopes and their respective half-lives. The accuracy of this age is dependent on whether or not the system remained closed. If thorium or uranium was incorporated into or exported from the sample after the initial uranium uptake, then the

resulting calculated age will be inaccurate. Diagenesis of aragonitic material to calcite is indicative of an open system (Thurber *et al.*, 1965). Candidates for Th/U dating should generally contain less than 5% calcite (D. Ford, written commun.).

Thermal-ionization mass spectroscopy (TIMS) is used to measure ^{230}Th and ^{234}U. $^{230}Th/^{234}U$ dating has an age limit of 50-500,000 years BP (Edwards *et al.*, 1987a; 1987b). Eleven samples from offshore cores BJC#1, 3 and 4 were analyzed by Dr. Derek Ford, McMaster University. Thirty-two onshore samples were gathered during two field trips (Nov. 17-27, 1999, and Feb., 2001) and analyzed by Claude Hillaire-Marcel (GEOTOP), Montreal, Quebec.

CHAPTER 2

PLEISTOCENE STRATIGRAPHY AND CARBONATE DATING

2.0 INTRODUCTION

The Ironshore Formation has traditionally been regarded as a single succession that was deposited during the Sangamon highstand ~125 ka BP (e.g., Emery, 1981; Woodroffe *et al.*, 1983; Jones and Pemberton, 1989; Jones and Hunter, 1990). A series of cores through the Ironshore Formation at Rogers Wreck Point, however, revealed four unconformity-bound units (A-D) (Vézina, 1997; Vézina *et al.*, 1999) that were separated from each other by paleosol horizons and calcrete crusts. Corals from units A, B, and C yielded ages that correspond to known Pleistocene highstands (Table 2.1). This led to a search for corroborating evidence on the rest of the island.

Table 2.1. Ages, relative sea levels, and corresponding marine isotope stages of Ironshore Formation units at Rogers Wreck Point (Vézina *et al.*, 1999).

Unit	Average age (B.P.)	Relative sea level (m)	Marine Isotope Stage
A	> 400, 000<< 1,500,000	-9.0 to –5.5	11?
B	346, 000	-3.0 to +0.5	9
C	229, 000	-2.5 to +1.1	7
D	131, 000	+2.5 to +6.0	5e

Unfortunately, previous attempts to explore the subsurface record of the western and central parts of Grand Cayman were unsuccessful because most of the Ironshore Formation in those areas is friable, and core recovery is extremely poor. Furthermore,

unconformities were not readily apparent in surface Ironshore Formation outcrops. Consequently, the stratigraphic relationships between exposures of the Ironshore Formation on the western part of Grand Cayman and units A to D in the Rogers Wreck Point area, on the northeast corner of Grand Cayman, were poorly understood.

The latest examinations and re-examinations of the western and central parts of the island have brought new stratigraphic clues to light. For example, coastal exposures of the Ironshore Formation near Salt Creek contain three hiatal surfaces (Jones and Pemberton, 1989). These surfaces were originally interpreted as channel diastems, based on their truncation of underlying laminations and lithofacies, topographic relief, and apparently localized extent. Since then, $^{230}Th/^{243}U$ dating of fossils from depositional packages between the surfaces has provided age control on those successions, confirming that at least one of the surfaces is an unconformity.

The succession at Rogers Wreck Point encompasses four stages of sedimentation that correlate with marine isotope stages 5e, 7, 9 and possibly 11 (Vézina, 1997; Vézina *et al.*, 1999). Changes over time in the oxygen isotope ratios in accumulating sediment can be used as a proxy for fluctuating Pleistocene global ice volume, and hence eustatic sea level (Shackleton, 1977). The high amplitude Sangamon highstand marks the substage 5e peak at ~125 ka BP (Imbrie *et al.*, 1984) on the SPECMAP time scale; it was succeeded by two smaller scale Pleistocene highstands (5a and 5c) during the interglacial stage 5. Evidence for the ~125 ka highstand is present on Grand Cayman in the Ironshore Formation as indicated by the presence of a wave-cut notch 6 m above sea level (Jones and Hunter, 1990). It is therefore reasonable to suggest that geological records of the ~105 ka and ~85 ka highstands (Imbrie *et al.*, 1984) may also be present

(Fig. 2.1). Due to the lower amplitudes of these later highstands, however, the actual evidence in the succession may not be as easily recognized. The reddish paleosols and calcrete crusts make the subsurface unconformities at Rogers Wreck Point easy to identify. Unfortunately, such features are not associated with the discontinuities found in outcrops on the western part of Grand Cayman, and no unconformities are apparent in the cores obtained from western offshore wells. Therefore, $^{230}Th/^{234}U$ fossil dating is essential in the recognition and delineation of depositional packages (Tables 2.2, 2.3, and 2.4).

2.1 ^{230}TH/^{234}U RELIABILITY REQUIREMENTS

$^{230}Th/^{234}U$ dating of fossils has been widely used for dating and correlating carbonate successions throughout the Caribbean (e.g., Osmond *et al.*, 1965; Mesolella *et al.*, 1969; Neef and Veeh, 1977; Schubert and Szabo, 1978; White *et al.*, 1998). Comprehensive reviews of uranium-series dating methods have been written by Ku (1976) and Ivanovich and Harmon (1982). Another such review is beyond the scope of this thesis; the following is merely a summary of the pertinent information.

$^{230}Th/^{234}U$ dating (hereafter referred to as Th/U dating) is a deficiency method based on the accumulation of ^{230}Th, a decay product of ^{234}U, in a closed system with an initial amount of uranium and no thorium. Marine invertebrates such as corals and molluscs routinely incorporate uranium into their skeletons in equilibrium with seawater. When the organism dies, its skeleton has a $^{234}U/^{238}U$ ratio equal to that of seawater (1.14 +/ - 0.03). The initial concentration of ^{230}Th in the skeleton is virtually zero because ^{230}Th has a low solubility and is quickly removed from seawater (Moore and Sackett, 1964). Uranium decay commences and its product, ^{230}Th, accumulates. Assuming

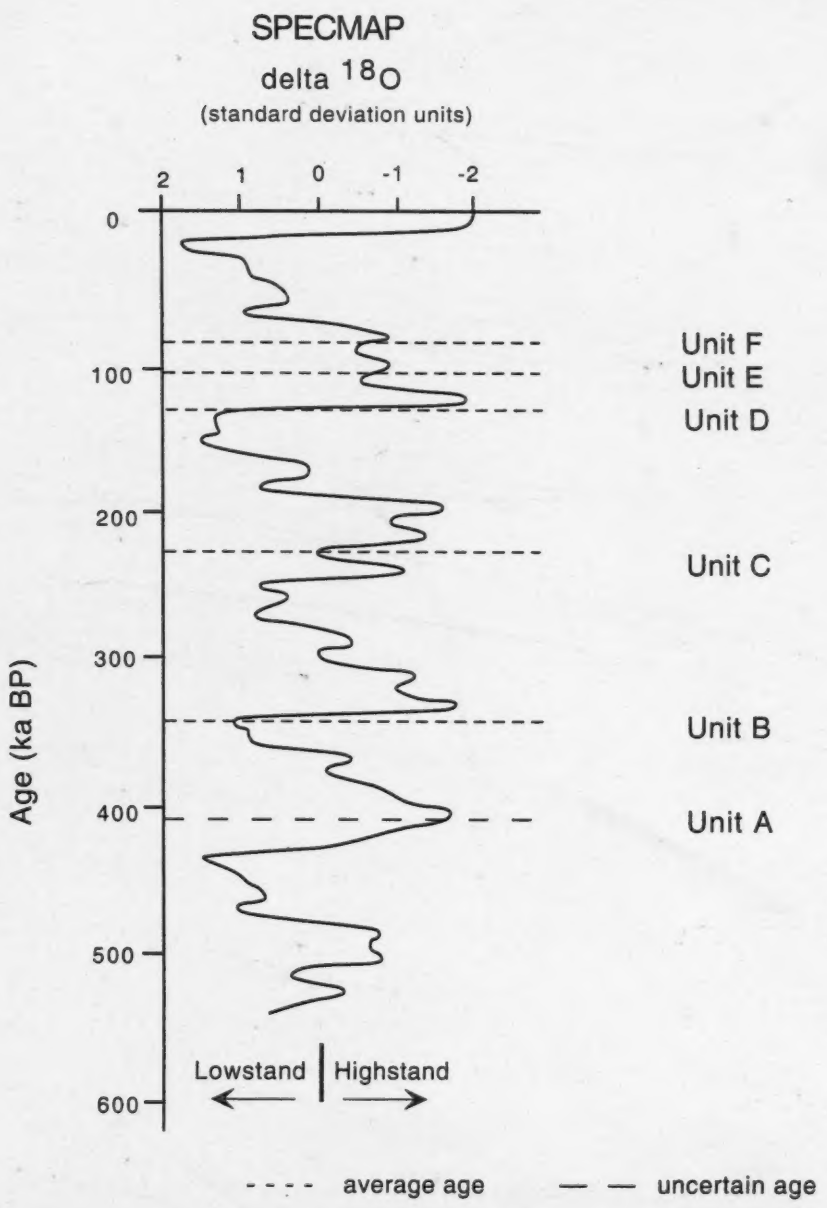

Figure 2.1. Correlation of dates from Units D, E and F (Ironshore Formation, Grand Cayman) with the SPECMAP time scale (modified from Imbrie *et al.*, 1984; Vezina, 1997; and Vezina *et al.*, 1999). The delta ^{18}O scale represents the isotopic fractionation of $^{18}O/^{16}O$ against a standard (ocean water = 0). Negative values represent ocean water enriched in ^{16}O (interglacial periods); positive values represent ocean water enriched in ^{18}O (glacial periods).

Table 2.2. $^{230}Th/^{234}U$ data and fossil ages from Rogers Wreck Point (Vezina,1997; and Vezina *et al.*, 1999). The age error is derived from the TIMS counting method statistics.

Sample	Coral species	Calcite (wt%)	[U] (ppm)	$^{234}U/^{238}U$	$^{234}U/^{238}U$ (initial)	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age (yr BP)	Age Error (2 sigma, years)	
									plus	minus
RWP#3	*Acropor a palmata*	0	3.16	1.099	1.191	0.903	13,500	232,000	5,600	5,300
RWP#6A	*Porites astereoides*	5.5	2.45	1.085	1.226	0.984	1,994	346,000	12,000	11,000
RWP#10	*Acropora palmata*	0	2.9	1.133	N/A	1.19	21,500	>400,000	N/A	N/A
RWP#13	*Acropor a palmata*	0	2.95	1.116	1.221	0.898	21,570	226,000	7,000	7,000
RWP#14	*Siderastrea sidera*	1.8	2.86	1.106	1.152	0.705	2,582	129,000	6,600	6,600
RWP#14	*Acropora palmata*	4.3	2.98	1.202	N/A	1.414	3,642	>400,000	N/A	N/A
RWP#15	*Siderastre a sidera*	2.3	2.69	1.114	1.166	0.72	1,707	133,940	1,590	1,590

Table 2.3. $^{230}Th/^{234}U$ data and fossil ages for three cores drilled off the west coast of Grand Cayman, George Town Harbour. The age error is derived from TIMS counting method statistics.

	Sample	Coral species	Calcite (wt %)	^{238}U (ppm)	$^{234}U/^{238}U$	$^{234}U/^{238}U$ (initial)	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age (yr BP)	Age Error (2 sigma, years)	
										plus	minus
Valid	BJC#1-52.0	*Acropora cervicornis*	10.4	3.1022	1.120246	1.15103	0.528625	306	80,137	1,611	1,580
Valid	BJC#1-53.0	*Montastrea annularis*	1.9	2.135	1.12244	1.16438	0.624501	539	103,727	2,093	2,053
Valid	BJC#1-62.0	*Montastrea annularis*	5	2.5197	1.11869	1.16241	0.648106	118	109,747	1,541	1,518
Valid	BJC#1-69.5	*M.ontastrea cavernosus*	3.9	2.4823	1.106012	1.1496	0.681829	1395	121,154	10,366	9,480
Valid	BJC#3-25.0	*Montastrea annularis*	4.1	2.59	1.15237	1.15505	0.054941	21	5,714	190	190
Valid	BJC#3-40.0	*Montastrea annularis*	7.4	2.4759	1.118862	1.16757	0.682849	486	120,915	2,046	2007
Valid	BJC#3-43.5	*Montastrea annularis*	0	2.382	1.11119	1.16295	0.722678	389	134,516	2,306	2256
Valid	BJC#4-44.8	*Montastrea annularis*	10.0	2.6145	1.116179	1.14613	0.530709	69	79,689	708	703
Valid	BJC#4-31.5	*Montastrea annularis*	1.8	2.8473	1.142065	1.14556	0.075851	52	8,327	125	125
Invalid	BJC#1-47.5	*Montastrea annularis*	1.9	2.487	1.1384377	1.364124	0.511862	261	69,101	1,445	1,431
Invalid	BJC#3-73.0	*Montastrea annularis*	6.6	2.4596	1.090448	N/A	1.43662	468	infinite age	N/A	N/A
Invalid	BJC#3-55.0	*Acropora palmata*	4.7	2.3234	1.131252	1.21982	0.832988	538	181,664	3,191	3,093

Table 2.4 Th/U data and ages for samples taken from Grand Cayman surface outcrops. Valid dates satisfy the specified criteria for a closed system.

	Sample #	Taxa	Calcite (wt%)	^{238}U conc. (ppb)	$^{234}U/^{238}U$	$^{234}U/^{238}U$ Error	Initial $^{234}U/^{238}U$	^{232}Th (ppb)	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age (yr BP)	Error (2σ)	
												plus	minus
Coral (valid)	TUF1,1,10.5'-14'	*M. annularis*	5.8	2957.6056	1.1124	0.0099	1.1684	8.7214	0.7436	857.336	142,526	3349	3222
	VDM4-1-99B	coral	2.1	2623.7833	1.1157	0.0069	1.1699	4.6914	0.7256	1383.745	135,698	5218	4962
	JP-2-99	*M. annularis*	4.2	2757.7318	1.1006	0.0089	1.1528	25.8589	0.7548	270.78	147,439	4083	3906
	PBQA-13-2001	*Porites* sp.	3.3	3353.0505	1.1001	1.0122	1.147	1.6095	0.7258	5084.175	136,340	3527	3380
	CLQ-3-2001	*M. annularis*	0	3095.2319	1.0907	0.0115	1.132	1.5186	0.7145	4854.858	132,615	3607	3457
	MH1-2' asl	*M. annularis*	0	2795.4582	1.1177	0.0076	1.1669	3.4218405	0.6894	1923.933	123,266	2711	2632
Coral (invalid)	TSE-12-2001	*M. annularis*	0	2701.2691	1.1263	0.0107	1.199	24.5265	0.7876	298.602	160,050	5029	4764
	JP-8-2001	*M. annularis*	0	2878.0226	1.1210	0.0085	1.176	2.70141	0.7190	2624.434	133,159	2903	2808
	VDM4-1-99	*M. annularis*	3.6	2793.2209	1.1268	0.0074	1.1828	21.7607	0.7076	312.774	129,030	3094	2995
	MH1-6" asl	*M. annularis*	0	3041.7158	1.1387	0.0072	1.1960	1.5798	0.6872	4604.594	121,995	2608	2536
Conch (valid)	LSC1-3-99	*Strombus gigas*	<3	776.9085	1.1222	0.0087	1.1564	1.8291	0.5573	811.876	86,931	3328	3219
	PBQA-2A-99	*Strombus gigas*	5.8	2351.2446	1.1013	0.0103	1.1338	1.9128	0.6017	2489.148	98,199	3465	3341
	PBQA-2B-99	*Strombus gigas*	10.6	922.299	1.0898	0.0095	1.1150	8.7078	0.5575	196.654	87,377	6569	6177
	PBQ-6-99	*Strombus gigas*	10.2	1347.5429	1.1216	0.0098	1.1557	2.1263	0.558	1212.32	87,102	2936	2848
	MAQ-9-2001	*Strombus gigas*	0	1467.7443	1.1233	0.0092	1.167	4.2053	0.6388	765.351	107,858	2821	2736
	CLQ-3-2001	*Strombus gigas*	0	1265.9513	1.1376	0.0085	1.169	1.2727	0.4994	1727.070	73,970	1182	1166
	CLQ-5-2001	*Strombus gigas*	0	1058.6384	1.0912	0.0103	1.114	0.9026	0.5224	2043.075	79,326	1983	1939
	CLQ-8-2001	*Strombus gigas*	0	1059.9093	1.1075	0.0089	1.14	1.6473	0.5895	1283.794	94,970	2780	2699
Conch (invalid)	SB-4-99	*Strombus gigas*	4.6	1092.7736	1.3215	0.0100	1.5182	2.0553	0.827	1775.884	168,373	4615	4414
	BQG-99	*Strombus gigas*	7.5	1465.2704	1.2363	0.0093	1.2819	2.2613	0.4425	1083.494	62,182	1408	1880
	PBQ-1-99	*Strombus gigas*	3.9	2756.8998	1.2007	0.0089	1.2870	4.6213	0.7051	1543.649	126,158	4867	4647
	PBQ-1-99	*Strombus gigas*	4.2	3373.4989	1.2295	0.0114	1.3289	4.7814	0.7099	1882.11	127,006	4617	4412
	TSE dredge	*Strombus gigas*	0	2986.56	1.2319	0.0096	1.3061	2.1086726	0.6082	3243.028	97,970	1730	1697
	JP-2-2001	*Strombus gigas*	0	1138.7846	1.0552	0.0099	1.073	0.6752	0.6074	3303.452	100,533	3045	2944
	LSCA-3-2001	*Strombus gigas*	0	1623.2096	1.1407	0.0083	1.197	4.2845	0.6757	892.414	118,348	2954	2863
	BL-2-2001	*Strombus gigas*	0	921.2598	1.4155	0.0116	1.797	0.2587	0.9476	14597.935	230,193	8455	7844
	PBQA-1-2001	*Strombus gigas*	0	385.2623	1.0674	0.0085	1.081	0.2881	0.4575	1995.774	65,997	2253	2201
	TSE-5-2001	*Strombus gigas*	0	1298.623	1.183	0.0091	1.260	22.8929	0.6971	142.975	124,026	7003	6595
	PBQ-9-2001	*Strombus gigas*	0	1305.7857	1.1725	0.0098	1.239	1.9496	0.6674	1601.912	115,126	2496	2427
Bivalve (invalid)	Omega dredge	bivalve	0	640.5297	1.238	0.0119	1.4151	4.6615604	0.8729	453.792	196,194	8879	8169
	VDM2 unit 3	bivalve	0	952.9209	1.4113	0.0126	3.8164	3.742181	1.1229	1233.326	678,620	447,940	169,530
	MH2 unit 1	bivalve	2.9	285.7379	1.4738	0.0160	2.1719	1.1067415	1.0464	1216.809	319,454	23,960	19,901

that the system remains closed, an accurate age can be obtained up until the time that the $^{230}Th/^{234}U$ ratio reaches equilibrium, according to the laws of radioactive decay. The following formula is used to calculate age (Edwards *et al.*, 1987b; Chen *et al.*, 1991):

$$^{230}Th/^{238}U = 1 - e^{-\lambda_{230}*t} + (^{234}U/^{238}U * 10^{-3})(\lambda_{230}/(\lambda_{230} - \lambda_{234}))(1 - e^{(\lambda_{234}-\lambda_{230})*t}) \quad (1)$$

where $^{230}Th/^{238}U$ = the measured present day activity ratio of ^{230}Th and ^{238}U,

$^{234}U/^{238}U$ = the measured present day activity ratio of ^{234}U and ^{238}U,

λ_{230} = the decay constant of ^{230}Th,

λ_{234} = the decay constant of ^{238}U, and

t = age of the sample in years.

Erroneous ages result from situations where post-depositional uranium or thorium migration from or into the system changes the isotope activity ratios. Therefore, this dating method must be approached with care. The reliability of each calculated date must be assessed using the following criteria:

1. Organisms such as corals and some molluscs grow aragonitic skeletons. When they undergo diagenesis, the aragonite is converted to calcite. High amounts of calcite usually indicate a breach in the integrity of the original closed system, resulting in carbonate recrystallization and isotope migration (Thurber *et al.*, 1965). Thus, samples with >3% calcite should not, under ideal circumstances, be used for dating. Samples with 3% to 5% calcite may be used if they are consistent with the stratigraphic data (D. Ford, person. commun., 2000). However, it should be emphasized that in practice, some samples with as much as 10% calcite still give acceptable ages, as long as they meet the rest of the criteria. Conversely, it is also

possible for a sample with 0% calcite to yield an invalid Th/U date. In this case, the isotope concentrations and activities must be examined for further verification.

2. The initial $^{234}U/^{238}U$ ratio of the sample should equal that of seawater, 1.14 +/- 0.03 (Ku *et al.*, 1977; L. Heaman, person. commun., 2001). This activity ratio is calculated using the formula:

$$A(^{234}U/^{238}U)_i = 1 + \{ [A(^{234}U/^{238}U)_{PD} - 1] / e^{\lambda_{234} * t} \} \quad (2)$$

where $A(^{234}U/^{238}U)_i$ is the initial isotope activity ratio, $A(^{234}U/^{238}U)_{PD}$ is the measured present day isotope activity ratio, λ_{234} is the decay constant of ^{234}U, and t is the previously calculated age (see equation 1) of the sample in years (Kaufman and Broecker, 1965). Values outside of the 1.14 +/- 0.03 range indicate a violation of the closed system assumption. Calculated ages with such values should be treated with caution.

3. The uranium content of a specific fossil carbonate sample should be similar to that of a modern sample, i.e. a fossilized *Acropora palmata* should be compared to a modern one (Thurber, 1965; Boom *et al.*, 1974; Ku, 1976). This also helps identify possible uranium migration, and is especially important when different types of organisms (that may incorporate significantly different amounts of uranium) are used. For example, Broecker (1963) found that the uranium concentrations of four unspecified modern corals ranged from 2.4 +/- 0.1 ppm to 3.0 +/- 0.2 ppm. Thompson and Livingston (1970) analysed 10 shallow water hermatypic corals from Florida and Jamaica (including *Meandrina areolata, Porites porites, Madracis mirabilis, Montastrea annularis, Scolmia cabensis, Phyllangia americana*) and determined their mean uranium concentration to be 2.88 +/- 0.42 ppm. No values were found for

modern *Strombus gigas*, although *Strombus raninus* contains < 0.01 ppm uranium (Broecker, 1963). Due to a paucity of species-specific data on uranium concentrations, the ^{238}U measurements for the fossils in this study were checked in a general way against the above values to ensure that there were no obvious discrepancies (e.g. a coral with 200 ppm uranium instead of 2 ppm).

4. The measurement of $^{230}Th/^{232}Th$ ratios provides a check for thorium migration. In a closed system, there should be no initial ^{232}Th or ^{230}Th because seawater usually contains very low concentrations of both isotopes. Meteoric water, however, has a $^{230}Th/^{232}Th$ ratio of 1 to 4 due to high amounts of detrital ^{232}Th. Therefore, high levels of ^{232}Th in a marine sample indicate that the sample has probably been contaminated with outside ^{230}Th (Thurber *et al.*, 1965). The $^{230}Th/^{232}Th$ cut-off is arbitrary. Thurber *et al.* (1965) recommended that a ratio of at least 20 is sufficiently high to guarantee a closed system (with respect to thorium migration).
5. When possible, the $^{230}Th/^{234}U$ age should be checked using another dating method. For example, ^{14}C dating methods can be used to verify samples less than 30,000 years old. This constraint is due to the relatively short half-life of C^{14} (Thurber *et al.*, 1965).

In this thesis, a *valid* or *acceptable* date is defined as one that meets the above criteria. However, it must be emphasized that a fossil age may still be considered valid, even if the first criterion (calcite percentage < 5) is not met. It should also be noted that the third criterion is not as strictly adhered to as the second. An *invalid* date is in direct violation of criterion 2.

2.2 Fossil evaluation and taxa-specific variations

Bivalves, corals, and conchs were collected from 24 surface outcrops, one onshore core, and four offshore cores in the Ironshore Formation (Fig. 2.2). To a large extent, collection was dictated by the types of fossils present in the strata. Corals were scarce in the uppermost exposed units on the western part of Grand Cayman, whereas conchs were not found in the lower units. Bivalves were found scattered throughout the strata, or concentrated in discrete layers. Th/U methods were used to date corals from the offshore cores (Table 2.3), and corals, conchs, and bivalves from the surface outcrops (Table 2.4). Their respective usefulness for Th/U dating is assessed below. Overall, corals gave the most reliable or valid ages, whereas the bivalves inevitably became open systems and yielded invalid ages. Some of the conchs provided acceptable ages.

2.2.1 Corals

Throughout the development of Th/U dating researchers have found that corals consistently give valid results (e.g., Broecker, 1963; Broecker *et al.*, 1968; Mesolella *et al.*, 1969; Bloom *et al.*, 1974; Bender *et al.*, 1979; Dodge *et al.*, 1983; Edwards *et al.*, 1987). In a summary of data from 16 other researchers (e.g., Broecker and Thurber, 1965; Thurber *et al.*, 1965; Osmond *et al.*, 1965; Veeh, 1966; Veeh and Chappell, 1970; Bloom *et al.*, 1974; Ku *et al.*, 1974; Neef and Veeh, 1977), Veeh and Burnett (1982) demonstrated that unrecrystallized fossil and modern corals have similar mean uranium contents of 2-3 ppm. In a separate survey of over 100 unrecrystallized corals, they found that 88% of the calculated initial $^{234}U/^{238}U$ activity ratios were within 2σ (0.04) of 1.14, the $^{234}U/^{238}U$ activity ratio of seawater. They concluded that uranium migration or uptake

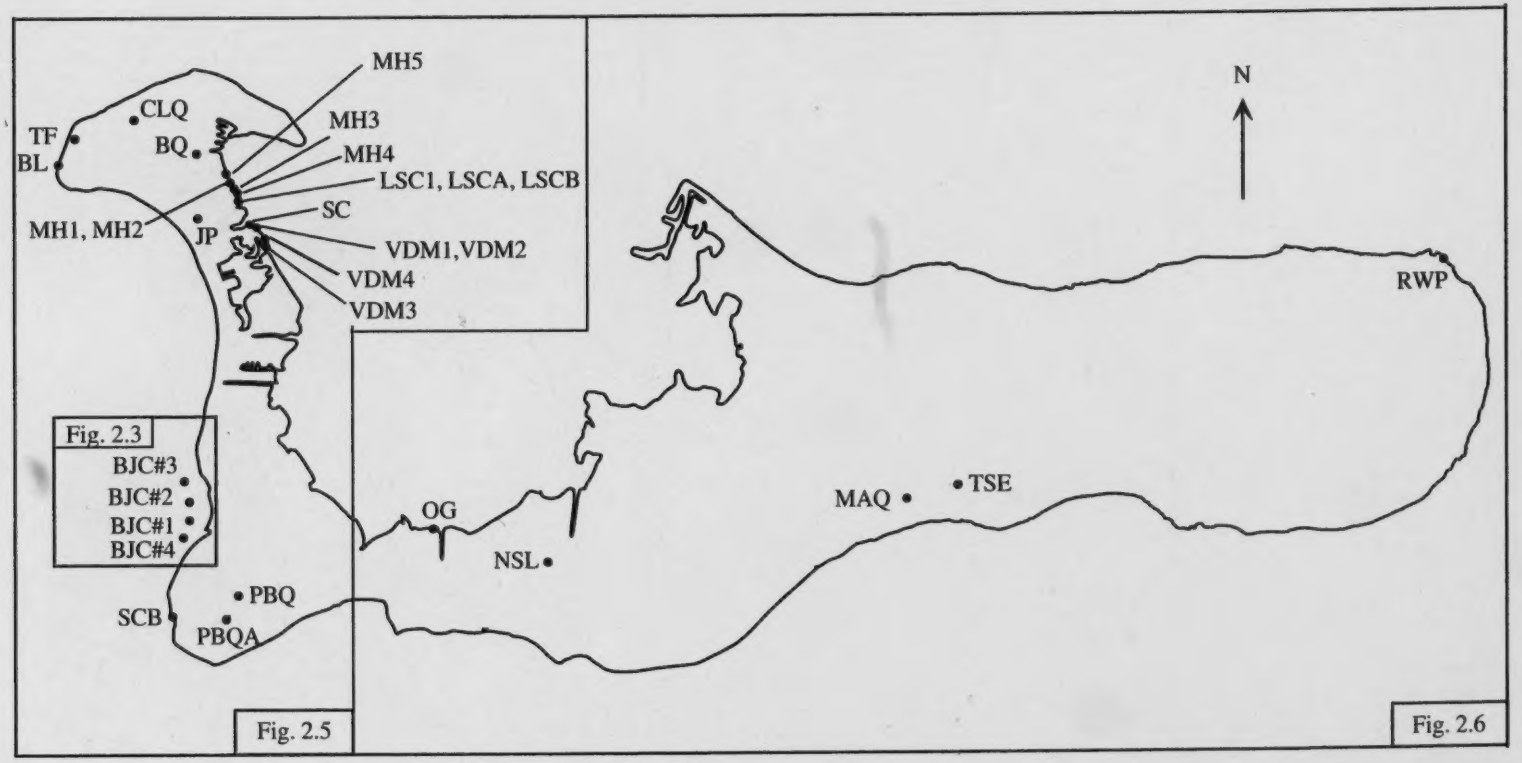

Figure 2.2. Fossil collection sites on Grand Cayman. See Appendix A for site abbreviations and precise locations.

is negligible in unaltered corals, and that reliable dates from corals can be obtained based on a closed system model.

Valid dates were obtained from nine of the twelve corals taken from the offshore cores (Table 2.3). Three corals had initial $^{234}U/^{238}U$ ratios that exceeded the expected sea water concentration of 1.14 +/- 0.03, and were therefore classified as invalid. Of the remaining nine corals, three exhibited calcite percentages between 5 and 10.4%. Although these are high values, these dates have been deemed valid because the isotope activity ratios and concentrations are within the closed system limits, and the stratigraphic order is logical (Fig. 2.3).

The ten onshore samples, with calcite amounts ranging from 0% to 5.8%, yielded six ages that fulfill the closed system requirements (Table 2.4). Others come close: at least two of the remaining four samples (VDM4-1-99 and JP-8-2001) have initial $^{234}U/^{238}U$ ratios within 0.05 of 1.14 and should probably not be rejected outright.

2.2.2 Strombus gigas (Queen conch)

Gustavsson and Högbert (1972) suggested that the inner cores of large, dense, well-preserved and unfractured molluscs would remain closed systems because their high density would ensure little isotope migration. Emery (1981) used the same reasoning when he collected aragonitic conch samples from the west coast of Grand Cayman. Nevertheless, the single date (~240 +/- 3ka) that he obtained from a *Strombus* shell was deemed too old because an independent isotope method ($^{231}Pa/^{235}U$) used to check the Th/U age indicated uranium loss from the sample.

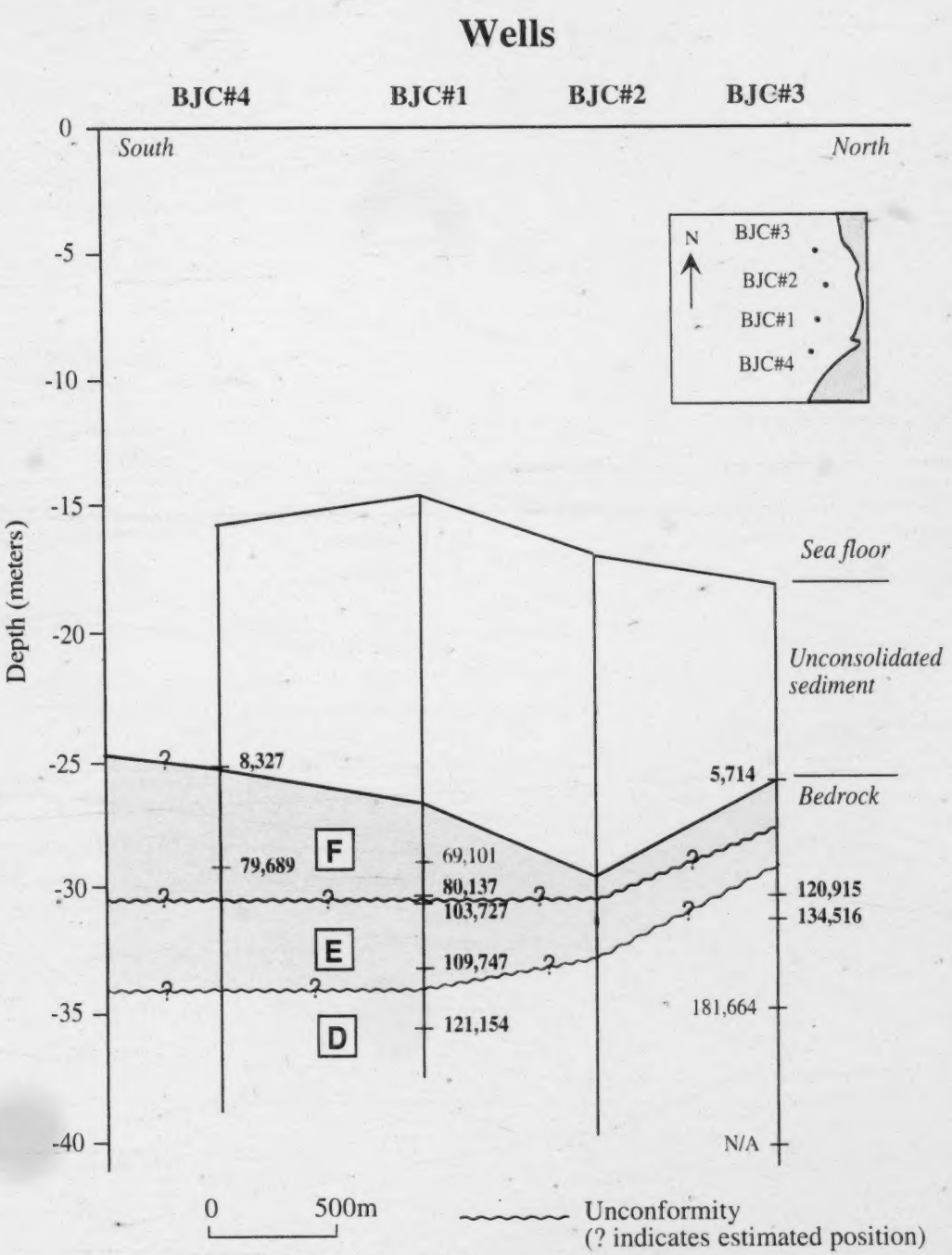

Figure 2.3. Section of four offshore cores recovered from George Town Harbour, west coast of Grand Cayman. Fossil coral Th/U dates are marked beside wells BJC#1, #3 and #4. Bold dates fulfill closed system requirements. Units D, E, and F are marked in bold print.

Sixteen conch shells were collected from various parts of the Ironshore Formation that either lacked corals or contained corals that had been substantially recrystallized. The conch shells were selected because they were not broken and appeared to be well preserved. Some of these shells even retained some of their original pink colouration.

The samples for analysis were carefully chosen from areas in the shell that contained the greatest density of aragonite. This was usually the lip of the conch, although in some cases the central core was the only usable portion.

Some complications became apparent after the samples were dated (Table 2.4). Eleven conchs contained 0% calcite, yet only four had initial $^{234}U/^{238}U$ ratios that matched that of seawater. Three of the four conchs were found in a single inland locality ~3 m above sea level (Canary Lane Quarry), not along the coast or from a dredge site. Of the other eight conchs, four yielded $^{234}U/^{238}U$ values within 0.03 of 1.14, and only one of the conchs contained less than 3% calcite. The two conchs with the highest percentages of calcite (10.8% and 10.2%) also yielded acceptable ages.

As age indicators, conchs must be treated with caution. Although individual samples may have 0 to 3% calcite the Th/U dates they yield can be inconsistent. There are no set criteria for identifying in hand sample the fossils that will give the most accurate dates. The information gained from *Strombus gigas* may be used as a supplementary source but should probably be used cautiously, and in conjunction with more reliable fossils, such as corals.

2.2.3 Other Molluscs

In contrast to corals, living molluscs generally contain much less uranium (Broecker, 1963; Blanchard *et al.*, 1967). This results in low initial $^{234}U/^{238}U$ ratios that make molluscs extremely susceptible to post-depositional uranium migration (Veeh and Burnett, 1982). The three bivalves collected from the upper part of the Ironshore Formation near Salt Creek yielded invalid dates of ~196 ka, ~679 ka, and ~320 ka years (Table 2.3). Although the $^{230}Th/^{232}Th$ ratios are well above 20, the calculated initial $^{234}U/^{238}U$ ratios of 1.41, 3.81 and 2.17, respectively, are significantly higher than the seawater value of 1.14. Clearly, these samples did not remain a closed system, and either gained uranium or lost thorium.

The tendency for molluscs to become open systems has been noted previously (Szabo and Rosholt, 1969; Szabo and Vedder, 1971; Kaufman *et al.*, 1971). In a study of 61 molluscs of known age, the Th/U dates were incorrect for 50% of them (Kaufman *et al.*, 1971). Kaufman *et al.* (1971) also noted that 25-30% of the samples >20,000 years old had higher uranium concentrations than samples <20,000 years old, and concluded that most but not all uranium uptake took place during the first 10,000 years after death. An open system model was developed (Szabo and Rosholt, 1969) but deemed unreliable because it was based on unrealistic isotope migration patterns (Kaufman *et al.*, 1971).

Bivalves were rejected for dating purposes because of the great uncertainty in the dates obtained.

2.3 Stratigraphy and Ages of the Ironshore Formation on West and central Grand Cayman

Cores from the Rogers Wreck Point area include Units A, B, C and D (Vézina, 1997; Vézina *et al.*, 1999). Th/U dates obtained from the surface outcrops and core, and offshore cores on the central and western parts of Grand Cayman provide evidence of Unit D, and two newly discovered younger units, E and F.

2.3.1 Offshore Grand Cayman

Aragonitic corals from wells BJC#1, BJC#3 and BJC#4 (Fig. 2.3) were dated, and acceptable ages were derived from all three cores. An age of 5,714 years was obtained from a coral just below the core/unconsolidated sediment interface in well BJC#3. Two dates of ~121 ka and ~134 ka were obtained 4-5 m directly below the unconsolidated sediment/bedrock interface. Corals from well BJC#1 yielded dates of ~80 ka, ~104 ka and ~110 ka, and ~121 ka (in order from shallow to deeper depths) (Fig. 2.3), and covered a total core length of ~7 m. The ~80 ka and ~104 ka dates were found < 1 m apart, indicating a time gap of 24,000 years. Two dates, ~80 ka and 8,327, were obtained from BJC#4.

The three oldest dates in the offshore cores ranged from 121 +/- 10 ka to 135 +/- 2 ka, with an average age of ~125 ka. These can be correlated with Unit D from the Rogers Wreck Point. The next youngest dates, 104 +/- 2 ka and 110 +/- 1.5 ka (average 107 +/- 2 ka), are separated from Unit D by a span of ~17 ka and form their own distinct unit, herein designated Unit E. This unit correlates with the 103-105 ka highstands recorded in Barbados (Broecker *et al.*, 1968; Mesolella *et al.*, 1969; Matthews, 1973;

Bender *et al.*, 1979), a 108 ka highstand from Haiti (Dodge *et al.*, 1983), and a 105 ka highstand in the Huon Peninsula, New Guinea (Bloom *et al.*, 1974; Aharon, 1983). The youngest coral ages, both 80 +/- 1 ka, are designated as part of the youngest unit, F. This unit can be compared to a 80 or 85 ka highstand recorded in the Huon Peninsula, New Guinea (Bloom *et al.*, 1974; Chappell, 1974; Aharon, 1983), a ~85 ka highstand in the Bahamas (Carew and Mylroie, 1987), a 81 ka highstand in Haiti (Dodge *et al.*, 1983), and a 82 ka highstand in Barbados (Broecker *et al.*, 1968; Mesolella *et al.*, 1969; Matthews, 1973; Bender *et al.*, 1979).

The single onshore well, TUF#1, had a coral ~143 ka old found 3 m below sea level. This may be from an older part of Unit D. All fossils below this depth were diagenetically altered and therefore undateable.

2.3.2 Salt Creek – Morgan's Harbour Area

The coastal Ironshore Formation exposed between Salt Creek and Morgan's Harbour is divided into lower and upper units by a well-developed discontinuity (Figs. 2.4, 2.5). The lower unit is characterized by bioturbated oolitic grainstones that lie between *in situ* patch reefs that are 5-15 m diameter. The upper unit is formed largely of cross-bedded oolitic grainstones that contain widely scattered corals, bivalves, and conch shells. The recrystallized corals in the upper unit could not be used for dating purposes. Two corals from the lower unit gave ages of 123 +/- 3 ka, and 136 +/- 5 ka (Fig. 2.5). One conch from the upper unit near Little Salt Creek yielded an age of 87 +/- 3 ka (Fig. 2.5).

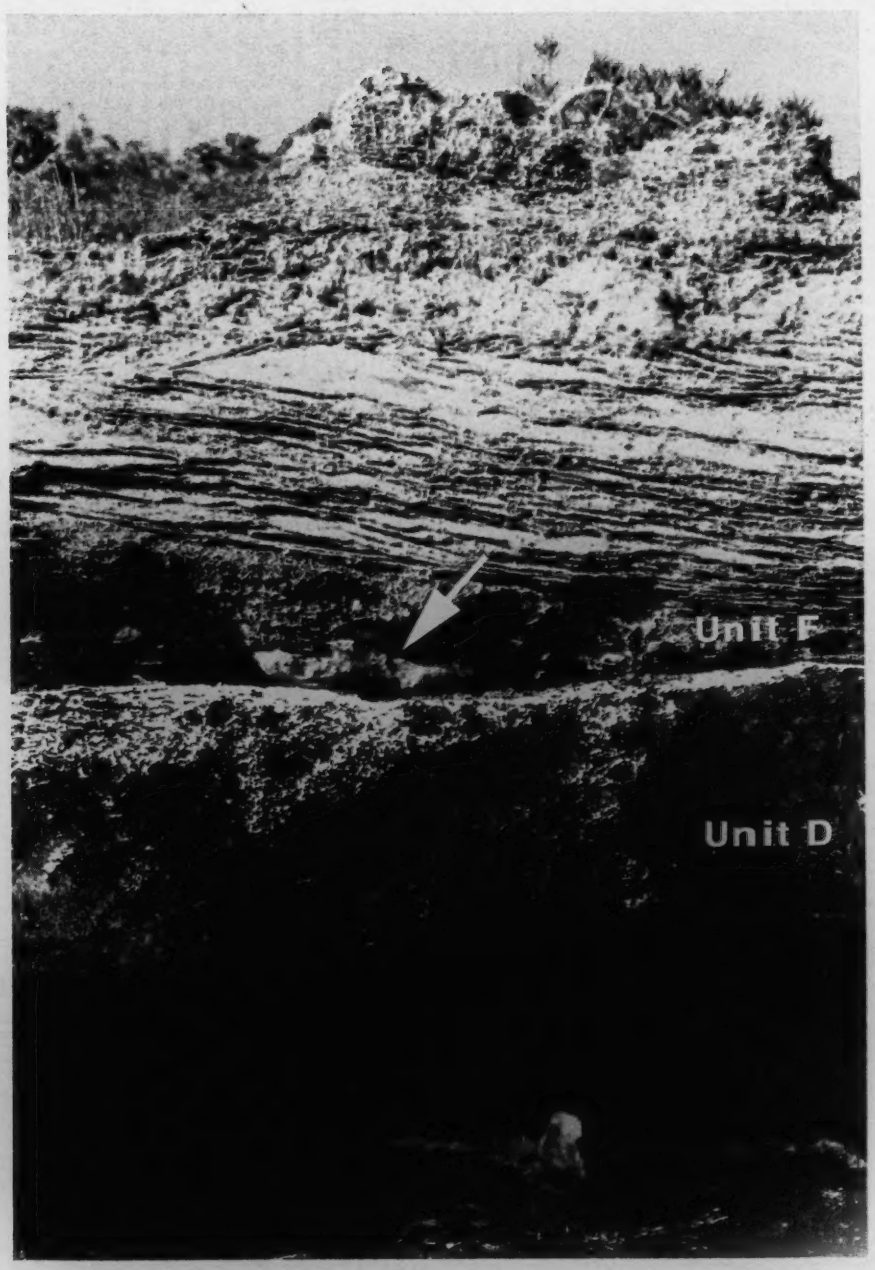

Figure 2.4. Section through units D and F, west coast of North Sound, near Salt Creek. Note tabular lithoclast resting on unit D. Note discontinuity between units D and F. Outcrop is about 2.5 m high.

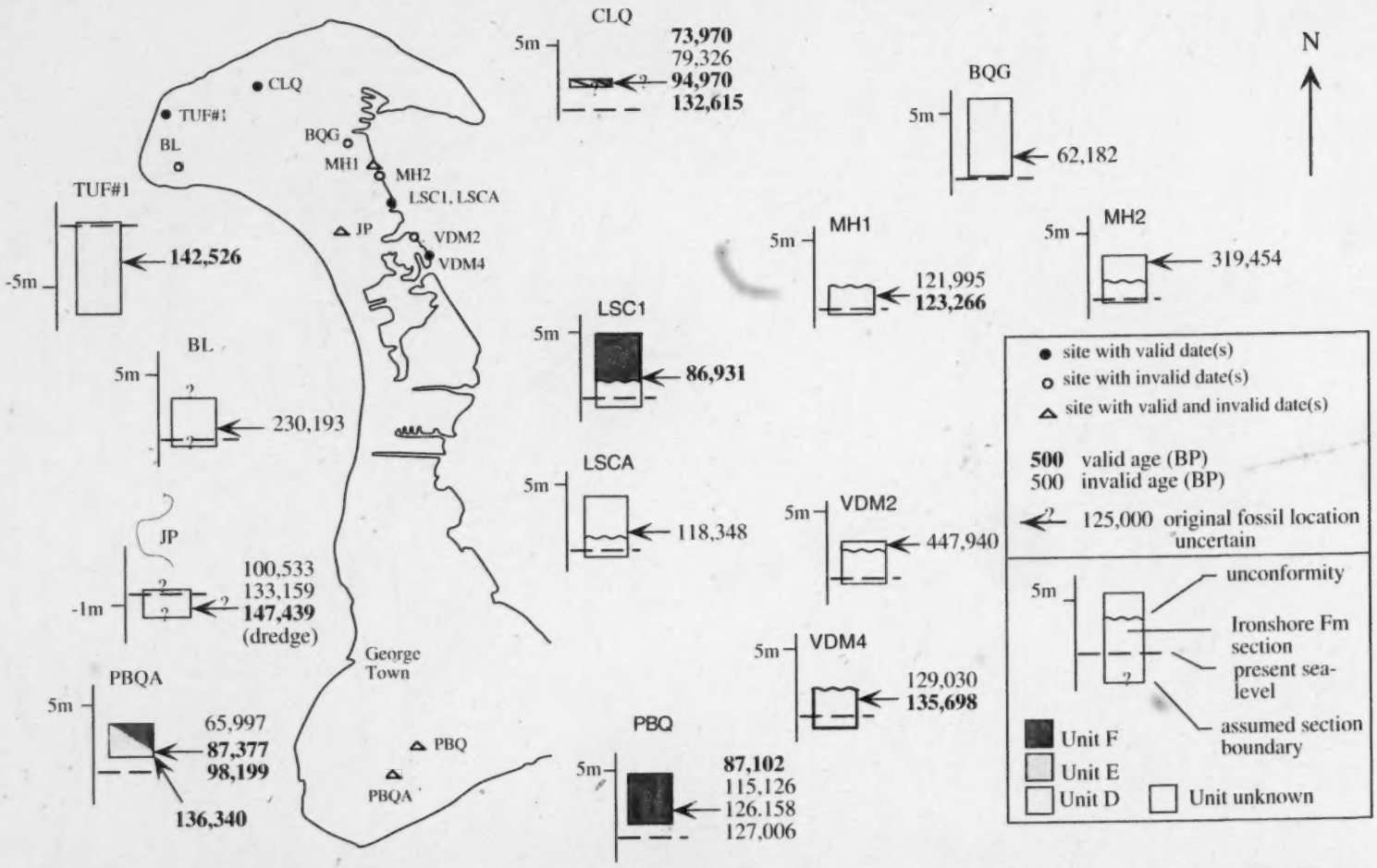

Figure 2.5. Diagram of west Grand Cayman with simplified Ironshore Formation sections. The Th/U fossil ages, both valid and invalid, from the dated sections have been included. Note that one site contains dredge conchs. Units D, E and F are shaded.

The dates for the lower and upper units indicate that the discontinuity is a major unconformity that represents a time gap of ~40,000 years. The lower unit, with an average age of 129 +/- 4 ka, is equivalent to Unit D of the Ironshore Formation as defined by Vézina (1997) and Vézina *et al.* (1999). The upper unit at Salt Creek, with an age of 87 +/- 3 ka, is younger than any of the units identified by Vézina *et al.* (1999). It is, however, close in age to Unit F as defined from core BJC#1. No fossils in the ~107 ka to 105 ka age range were found. Thus, unit E appears to be missing from the succession exposed on the west coast of North Sound. The sharp, well-defined unconformity at the base of Unit F is indicative of a major erosion surface. Unit E may have been deposited and then completely removed by erosion.

2.3.3 Paul Bodden Quarries

Localities PBQ and PBQ-A are located inland from the south and west shores of Grand Cayman (Fig. 2.5). At PBQ, the Ironshore Formation rests unconformably on the Cayman Formation. There are no sharp discontinuity surfaces in the Ironshore Formation at PBQ or PBQA. At both localities, however, scattered *Porites* thickets in the lower part of the sections are overlain by cross-bedded oolitic grainstones. Conchs are found above the *Porites* thickets at both localities, and resting on the Cayman-Ironshore Formation unconformity surface at PBQ. One date, 136 +/- 3 ka, was obtained from *Porites* in the lower part of the PBQ-A section. Conchs from the upper part of the succession at PBQ-A yielded ages of 87 +/- 6 ka and 98 +/- 3 ka. One conch at PBQ gave a date of 87 +/- 3 ka. It is most likely that the disconformity at each locality is represented by the *Porites*/grainstone facies change. Thus, the ~136 ka and ~87 ka dates can be assigned to

Units D and F, respectively. The ~98 ka date may be an older part of Unit F, or a younger part of Unit E.

2.3.4 Central Grand Cayman

One coral, four conchs, and one bivalve from the dredge sites and quarries on the central part of the island (Fig. 2.6) were dated. Although well preserved, only one conch from Midlands Acres Quarry yielded a reliable date of 108 +/- 3 ka. This fossil provides additional evidence for Unit E, along with the 104 ka and 110 ka, and possibly the 98 ka and 95 ka ages from offshore well BJC#1 and PBQ-A, respectively.

2.3.5 Canary Lane Quarry

The Ironshore Formation is exposed in a small quarry northwest of Morgan's Harbour (Fig. 2.5). The quarry floor is ~2 m above sea level and its walls are 0.8 m to 2.4 m high. Scattered blocks of Cayman Formation on the floor suggest that the boundary between the Ironshore Formation and the Cayman Formation is just below the surface. There is no visible disconformity, but there is a facies change similar to the Botabano Quarry and Salt Creek areas. Scattered coral colonies and conchs, and heavily bioturbated sediment in the lower meter are overlain by planar to low angle oolitic grainstone with only scattered fossils.

Loose conchs and *in situ* corals were collected for dating. Four acceptable ages of 74 +/- 1 ka, 79 +/- 2 ka, 95 +/- 3 ka and 133 +/- 3.5 ka were obtained from three conchs and one coral. The coral (133 ka) belongs to Unit D, and the conch ages are indicative of unit F.

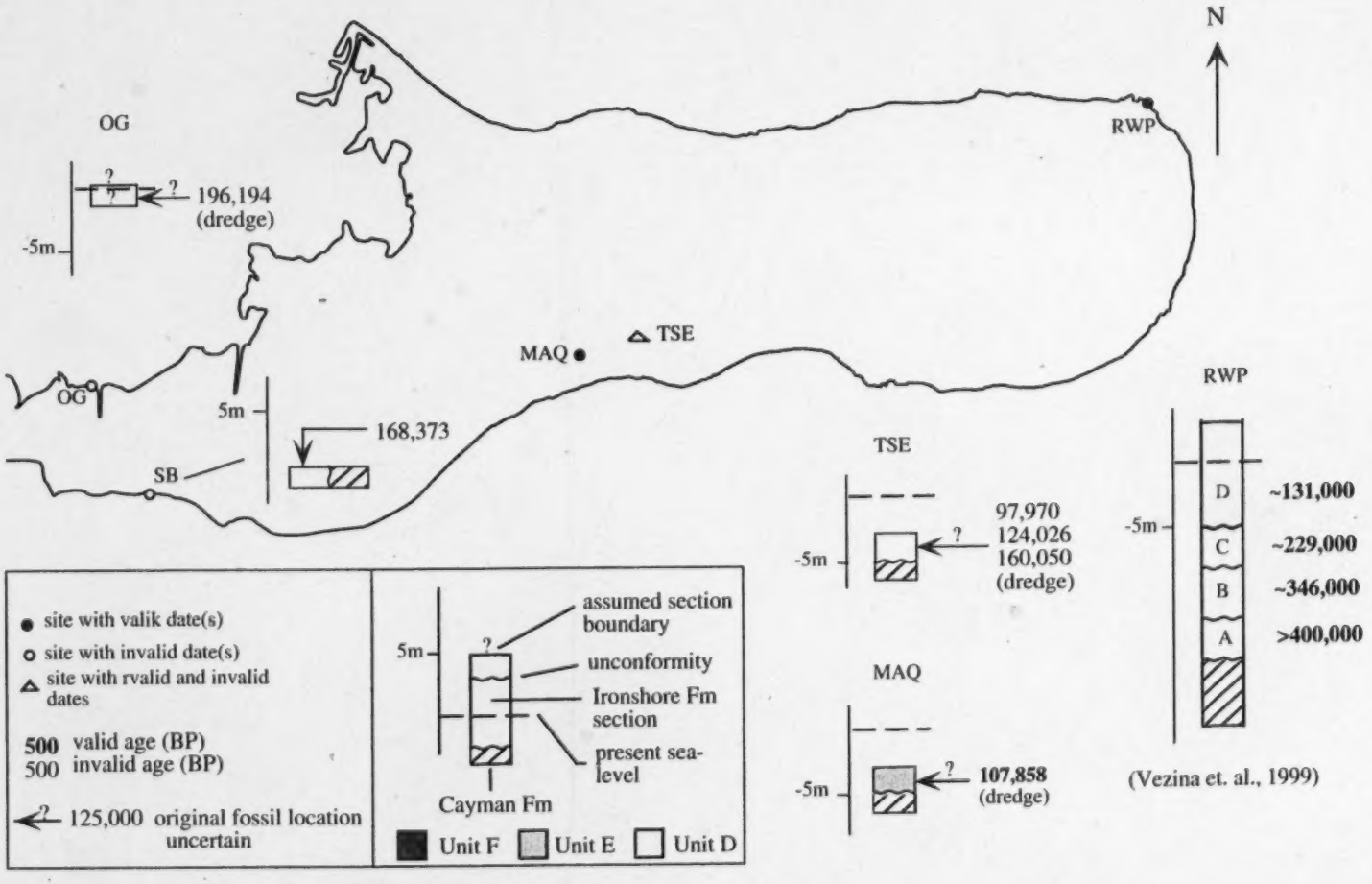

Figure 2.6. East Grand Cayman with simplified Ironshore Formation cross-sections from five locations. Th/U fossil ages are shown on the cross-sections . The Rogers Wreck Point section was modified from Vezina *et al.* (1999).

2.4 SYNOPSIS

Three units, D, E, and F exist on the western offshore, and west and central onshore Grand Cayman. Most of the evidence for unit E lies in the offshore cores. The mean unit ages are ~133 ka, ~101 ka, and ~80 ka, respectively. The range of these ages and what they represent will be discussed further in Chapter 4.

CHAPTER 3

FACIES ARCHITECTURE OF THE GEORGE TOWN OFFSHORE CORES

3.0 INTRODUCTION

The leeward western coast of Grand Cayman Island lacks the fringing reefs found along the windward south and east coasts (Darbyshire *et al.*, 1976; Blanchon, 1995; Blanchon and Jones, 1997). This allows for the easy access of large sea vessels, notably cruise ships that anchor daily in George Town harbour. Although beneficial to the island's tourist economy, the constant sea traffic coupled with indiscriminate anchoring has led to the degradation of some deep water reef environments. In an effort to minimize future damage of this type, the Cayman Port Authority investigated the possibility of building permanent mooring piles in the George Town harbour. Thus, from October 26–30, 1996, Fugro-McClelland Marine Geosciences Inc. and Moffatt & Nichol International (M & N) undertook an offshore exploratory drilling and testing program of four proposed mooring locations. The four cores that were retrieved are geologically significant for the following reasons:

1. They are only the second set of Ironshore Formation cores to be drilled with >50% recovery (the first set was recovered by Vézina, 1997). Other attempts to core the Ironshore Formation have failed because of the friable nature of the rock.
2. They are the first long cores from the Ironshore Formation that are located offshore. All previous work on the Ironshore Formation has examined onshore or near-shore material (Rigby and Roberts, 1976; Blanchon, 1995; Kalbfleisch, 1995; MacKinnon, 1999; Beanish, 2000). These offshore cores are significant

because they represent possible new environments which may result in a better understanding of the deposition of the Ironshore Formation.

3. The cores contain well-preserved corals that can be dated using the Th/U system (detailed analysis is provided in Chapter 2).
4. The ages obtained from the fossils allow correlation between offshore and onshore successions.

3.1 Facies Description of George Town Harbour Cores

The four cores were drilled in water 15-18 m deep. The rock from which the cores were retrieved was mantled by an unconsolidated sediment blanket, 7-12 m thick (Table 3.1). Five facies, delineated on the basis of biota and lithology, are present in the Ironshore Formation found in these cores. Corals were identified with the aid of photographs in Hunter (1994) and Humann (1998), and other organisms by comparison with photographs in Scholle (1978).

Table 3.1 Water depth, sediment and core thickness for off shore cores BJC #1-#4.

	BJC #1	BJC #2	BJC #3	BJC#4
Water depth (m)	14.5	17.0	18.2	15.8
Sediment thickness (m)	12.1	12.7	7.6	9.6
Core length (m)	10.8	10.0	15.2	13.3
Core recovered (m)	9.6	5.5	12.6	9.2

3.1.1 Facies 1: Head coral floatstone

This facies is dominated by *Montastrea annularis* along with fewer *Diploria* sp. and *M. cavernosa* (Fig. 3.1). Corals are either large (up to 0.5 m long and entire width of core) with practically no alteration to calcite, or poorly-preserved fragments 3-6 cm long.

The former probably represent *in situ* corals, given that the coral heads are not broken, their corallites are oriented towards the top of the core, boring is minimal (usually limited to *Lithophaga*), the coral chambers are usually empty, and red algal encrustations are limited to the top of the head. By contrast, the coral fragments are partially encrusted with red algae, their chambers are usually filled with fine to muddy dark brown micrite, and they are much more extensively bored and abraded than the head corals. The fragments probably had a longer residence time on the sea floor, and were therefore more prone to physical and biological erosion, and/or transportation.

The matrix is typically a skeletal grainstone, less commonly a packstone or wackestone. The grains are usually poorly sorted, sub-angular to sub-rounded, and range in size from very fine to very coarse sand, but have an average medium to coarse sand size. The skeletal grains are derived from red algae, benthic foraminifera (including *Homotrema*), echinoderm spines, mollusc and *Halimeda* fragments, serpulids, peloids, and various other unidentified (micritized) allochems. Composite grains are rare. Disarticulated bivalve and gastropod shells, usually retaining their original colouring, are common. Abiotic sedimentary structures are not present, but some horizontal bioturbation is present in the muddy patches.

3.1.2 Facies 2: Branching coral floatstone

Fragments of *Acropora cervicornis* and *A. palmata* dominate this facies (Fig. 3.2 A, B), with fewer *Porites* sp. and *Manicina*. Most, if not all, of the corals appear to have been moved from their original growth positions. There are no concentrated layers of a single species, and all of the corals are fragmented. The *A. cervicornis* fragments, which

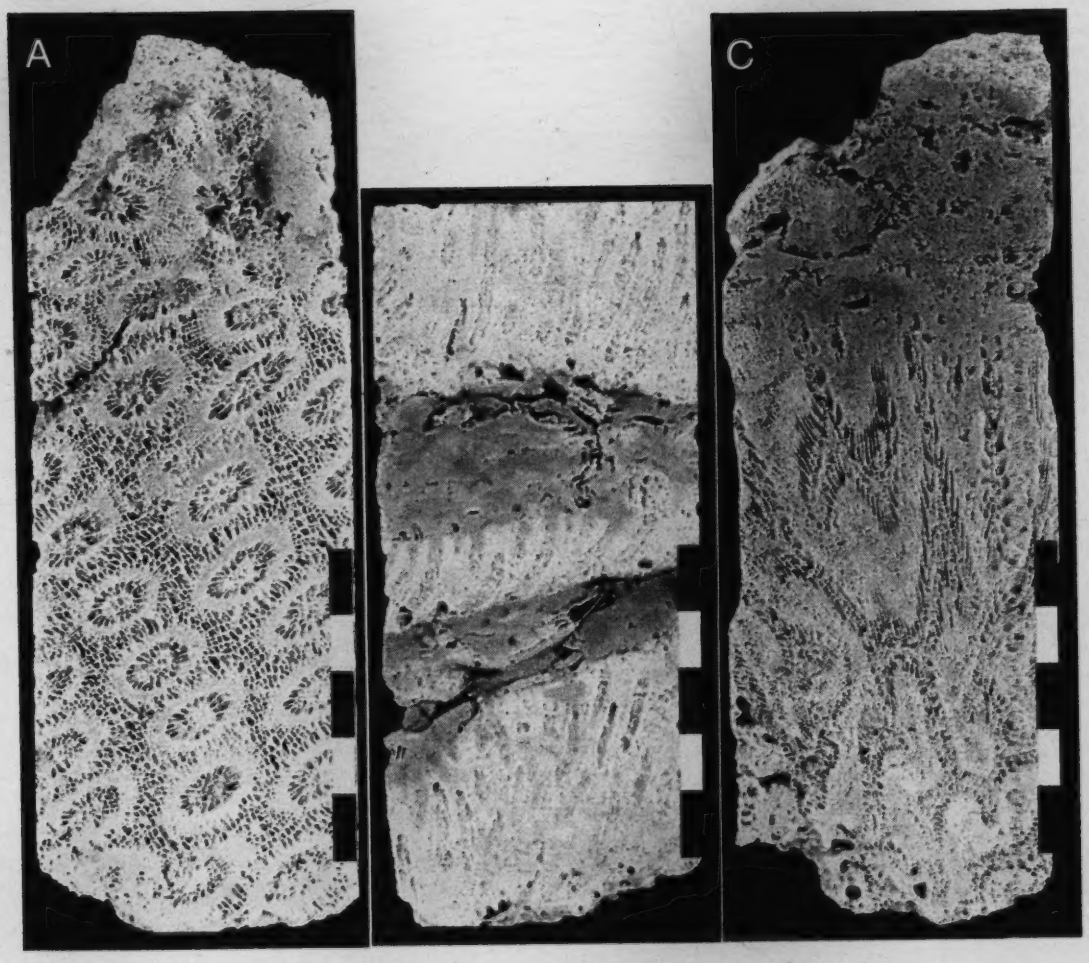

Fig. 3.1. Head coral floatstone facies. (A) *Montastrea cavernosa*. (B) *Montastrea annularis* (ma) with packstone layers (pk). Note *Halimeda* plates (ha). (C) *Diploria* sp. Each scale division is 1 cm long.

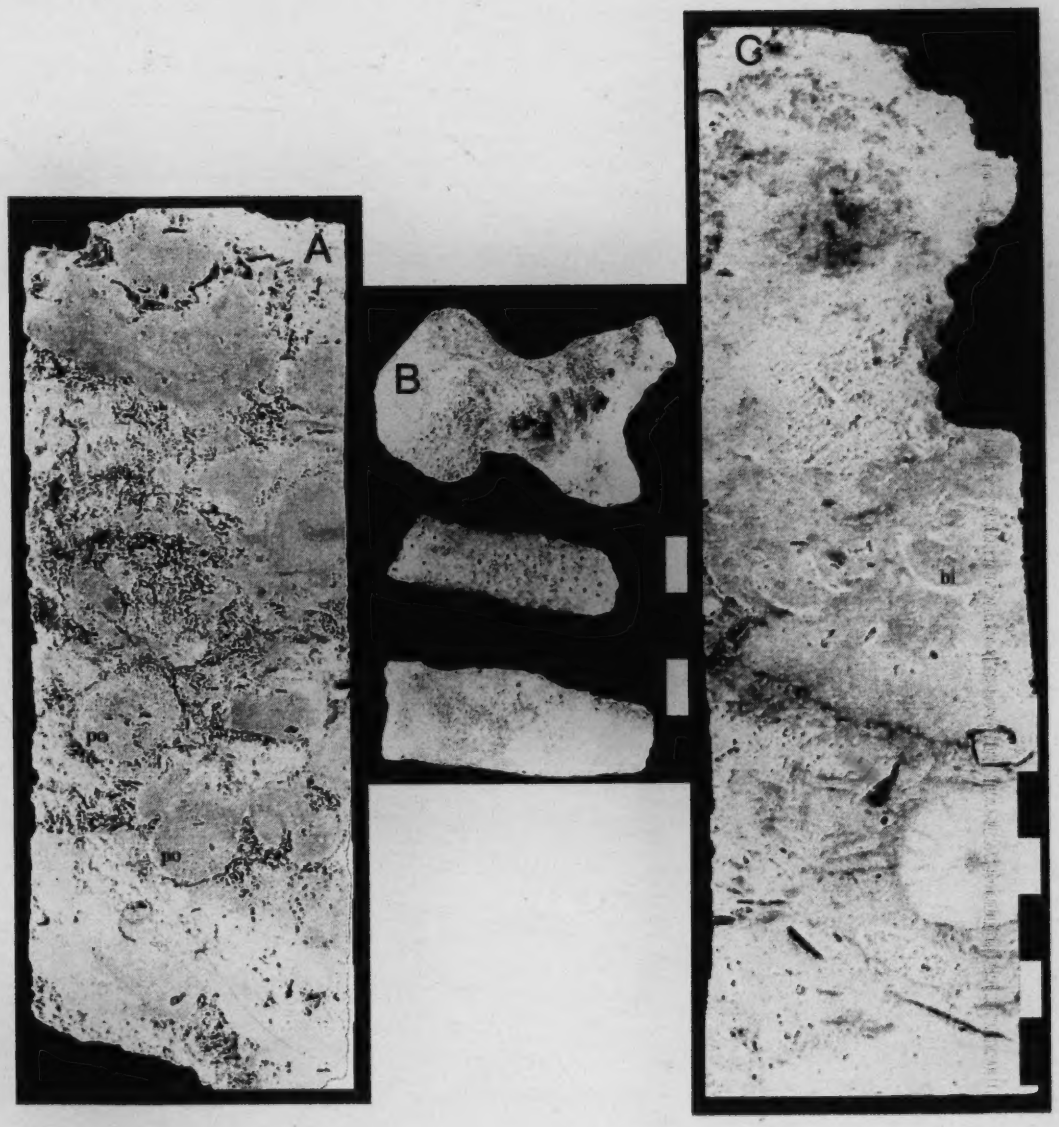

Fig. 3.2 Branching coral floatstone facies (A and B), and mixed coral floatstone facies (C). (A) Skeletal grainstone matrix with Porites sp. (po) and Acropora palmata (ap). (B) Acropora cervicornis fragments. (C) Skeletal grainstone matrix with bivalves (bi) and fewer corals than A. Each scale division is 1 cm.

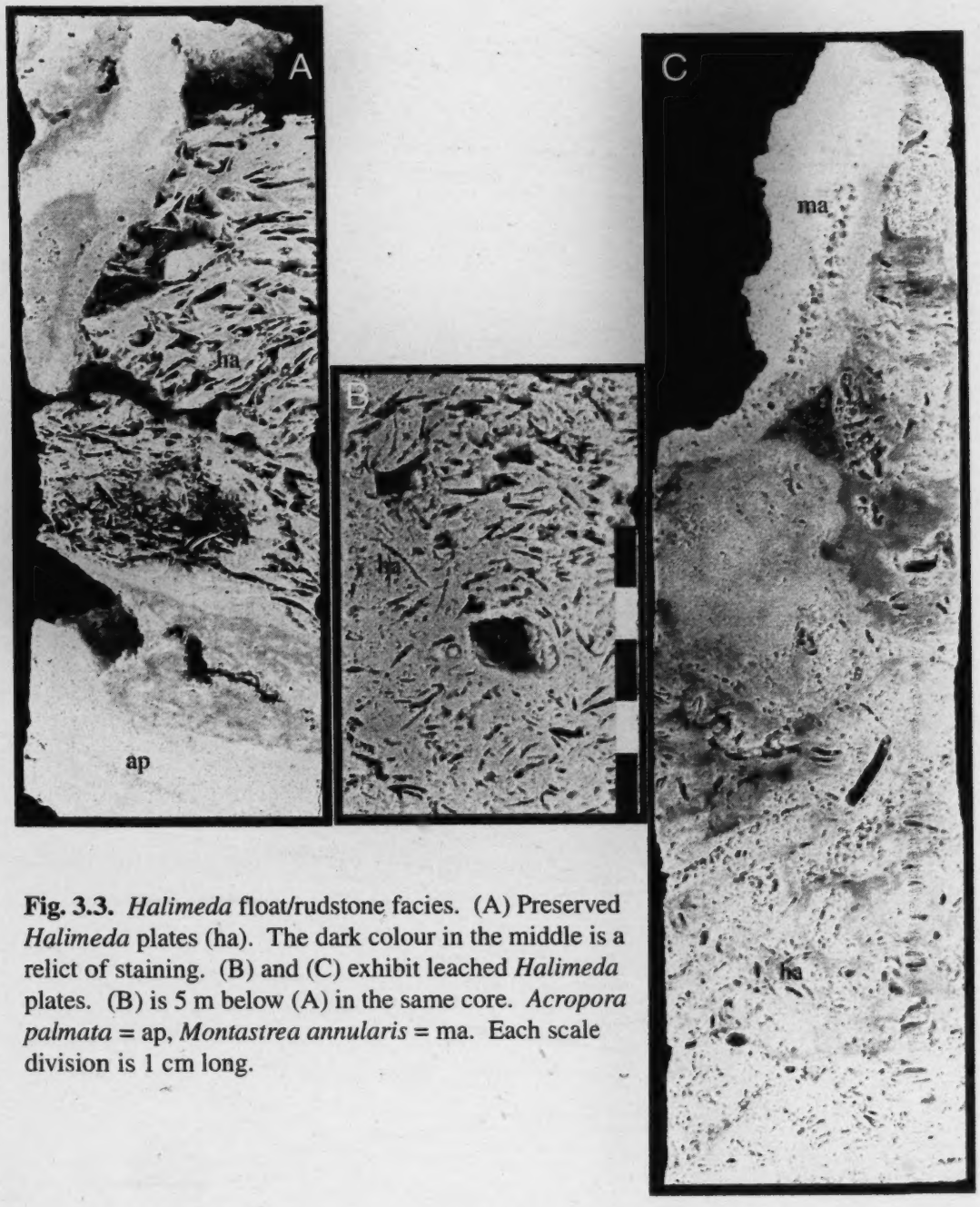

Fig. 3.3. *Halimeda* float/rudstone facies. (A) Preserved *Halimeda* plates (ha). The dark colour in the middle is a relict of staining. (B) and (C) exhibit leached *Halimeda* plates. (B) is 5 m below (A) in the same core. *Acropora palmata* = ap, *Montastrea annularis* = ma. Each scale division is 1 cm long.

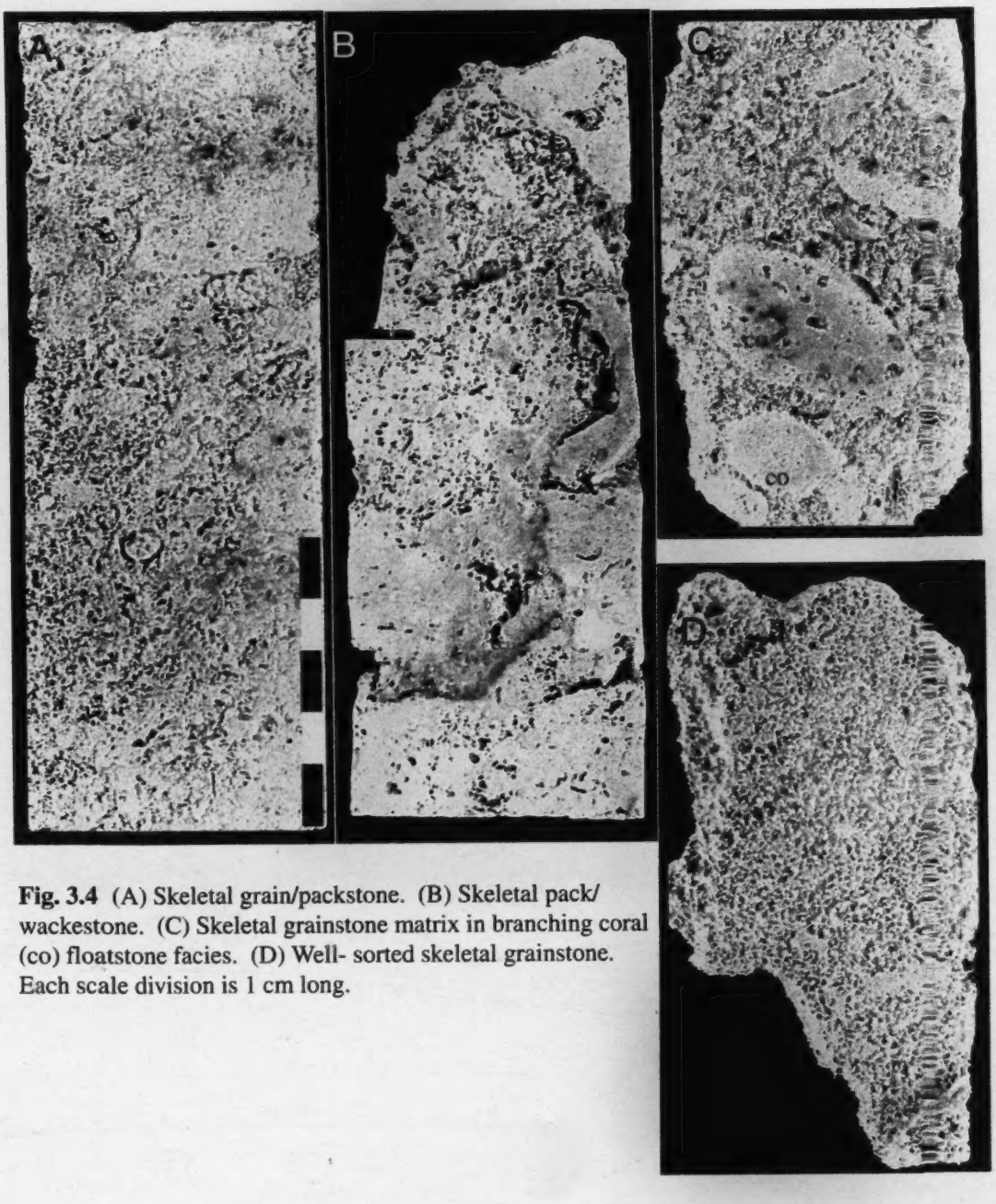

Fig. 3.4 (A) Skeletal grain/packstone. (B) Skeletal pack/ wackestone. (C) Skeletal grainstone matrix in branching coral (co) floatstone facies. (D) Well- sorted skeletal grainstone. Each scale division is 1 cm long.

are1-4 cm long and 0.5-2 cm diameter, usually have a horizontal orientation. Within a 10 cm long core section from BJC#3, the coral fragments demonstrate different stages of preservation. Some pieces are partially encrusted with red algae and *Homotrema*; their interior cores are leached and filled with micrite, and the outer surfaces are heavily bored and micritized. Other pieces lack a red algae coating, and are unaltered with little to no boring. This indicates that they spent little time on the seafloor where they would be available to boring and encrusting organisms.

The matrix is similar to that in the head coral floatstone facies.

3.1.3 Facies 3: Mixed coral floatstone

This facies contains large head and branching corals, including *Acropora cervicornis, A. palmata, Montastrea annularis, Porites* sp., *Diploria strigosa, D. labyrinthiformis, D. clivosa, Agaricia fragilis* (?), and *Siderastrea* sp. (Fig. 3.2 C). These fragmented corals, < 8 cm long, exhibit various amounts of boring and red algal encrustation. As in the branching coral floatstone, the fragmented corals most probably represent many cycles of transportation, deposition and reworking. The matrix is similar to that in the head coral floatstone facies.

3.1.4 Facies 4: Halimeda float/rudstone

This facies is comprised of 40-70% *Halimeda* plates (Fig. 3.3). In BJC#3, between depths of 25 m and 30 m, the unfragmented, 0.4 to 1 cm long, whitish plates are well-preserved. 10 to 30% of the interior pores are either leached or else leached then filled with clear equant cement or muddy sediment. Below 30 m, at least 70% of the

Halimeda plate interiors have been completely leached, and only the molds remain. The plates are loosely packed in a horizontal to 40° orientation, although plates tilting up to 70° are also present. Discrete stacks of 4-6 plates that are commonly imbricated are present. The matrix ranges from skeletal wackestone to grainstone, with a maximum average grain size of medium sand. Disarticulated, 1-2 cm long bivalves (fragmented and/or displaying their original colour) are common. There are no broken coral pieces, but *in situ* laminar *M. annularis* are present near the bottom of BJC #4.

3.1.5 Facies 5: Skeletal grain/pack/wackestone

This facies is characterized by poorly sorted, sub-rounded to sub-angular to angular, very fine to very coarse sand-sized skeletal grains that are formed of red algae, echinoid spines (particularly purple *Diadema*), mollusc, *Halimeda* fragments, *Homotrema*, and assorted benthic foraminifera (Fig. 3.4). There are scattered composite grains. These sediments are devoid of physical structures apart from subtle upward-fining over a meter-long scale. The muddier rock exhibits some bioturbation. These range from horizontal traces < 0.5 cm in diameter, to vertical burrows with horizontal side chambers. The grainstones commonly contain scattered molluscs that retained their original colouring. Bivalves are disarticulated, fragmented, and up to 5 cm long. Gastropods are less common. In general, the shallower parts of the core are poorly cemented. Thus, it was impossible to obtain thin sections for some grainstones because the rock disintegrated under the rock saw blade.

This facies exists as a distinct facies and as a matrix for fossil floatstones and rudstones.

3.2 INTERPRETATION

The four cores are located along a ~ 2 km transect that is parallel to the shore. The core facies and ages are not laterally consistent across the four boreholes (Fig. 3.5). BJC#2 contains the greatest thickness of skeletal grainstones; BJC#1 is predominantly head coral floatstone, and BJC#3 is a mixture of all facies but contains the most *Halimeda* float/rudstone. Both of the dated cores (BJC#1 and BJC#3) yielded corals 121 ka old, and there is a 5 m difference in relief between the positions of those two corals. Interpretation of the past environments can be partially extrapolated by comparison to Grand Cayman's modern marine environments.

Grand Cayman lies in the Northeast Trade wind system, with easterly or south-easterly winds in the wet season (May to November) and easterly and north-easterly winds in the dry season (December to April). Ocean currents and wind-generated currents contribute significantly to the total water energy because the shelf is narrow (extending up to 1 km from shore) and the tidal range minimal. Hence, the shores with an easterly component receive the most wave energy, and shores with a westerly component are more sheltered. The island can be divided into three zones based on shore water energy: the *exposed-windward margin*, the *protected-windward margin*, and the *leeward margin* (Blanchon, 1995; Blanchon and Jones, 1997) (Fig. 3.6). Each margin exhibits differences in morphology and biota.

Blanchon (1995) noted that the Cayman shelf had three basic sections regardless of margin: an upper-shelf terrace (0-10m below mean sea level), a mid-shelf scarp (10-20 m below msl), and a lower-shelf terrace (15-30 m below msl). In wind-facing areas a mid- shelf scarp notch at –18.5 m msl is visible; in sheltered areas the scarp is usually at

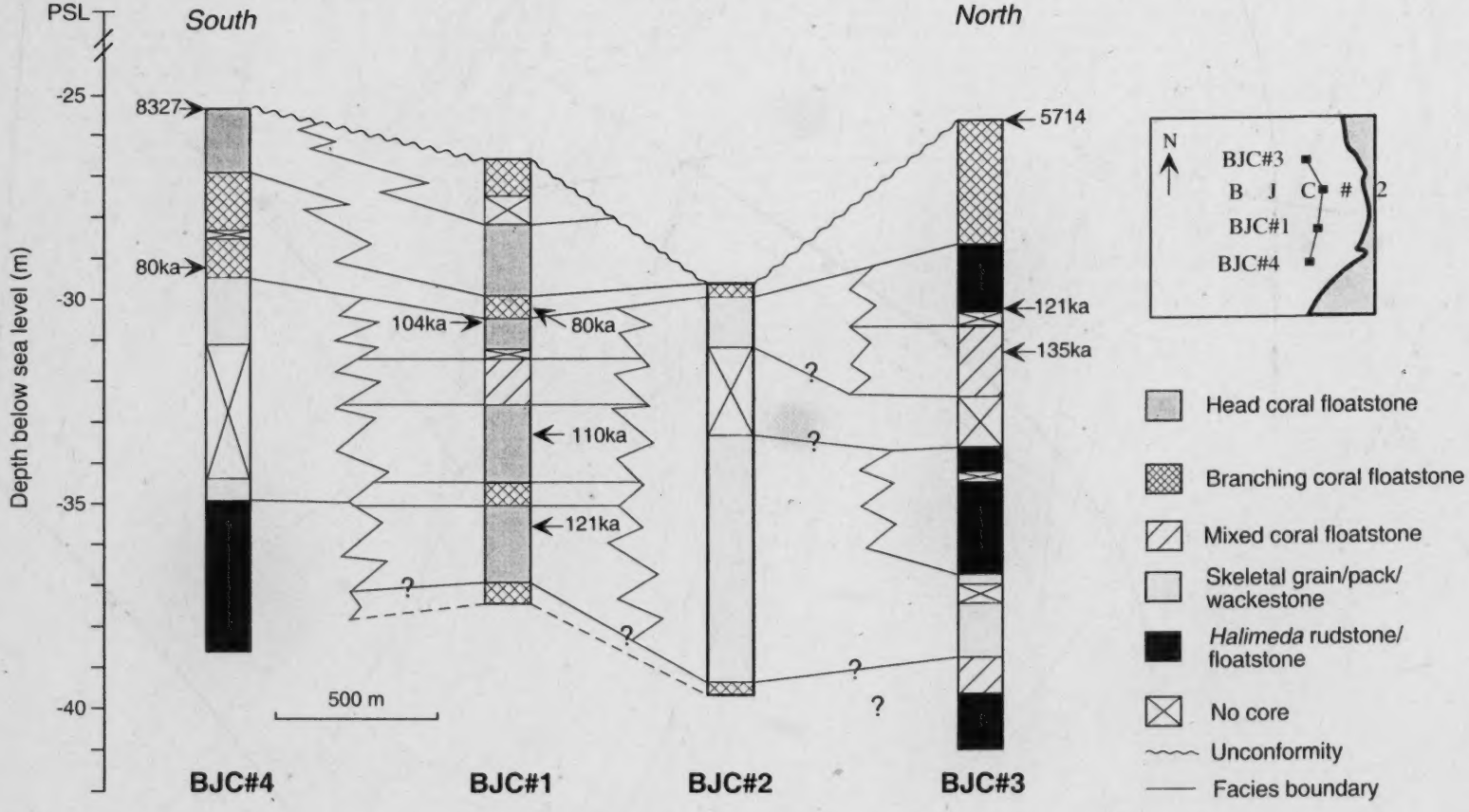

Figure 3.5 Biofacies correlation of four offshore cores from Georgetown Harbour. Datum is present day sea level.

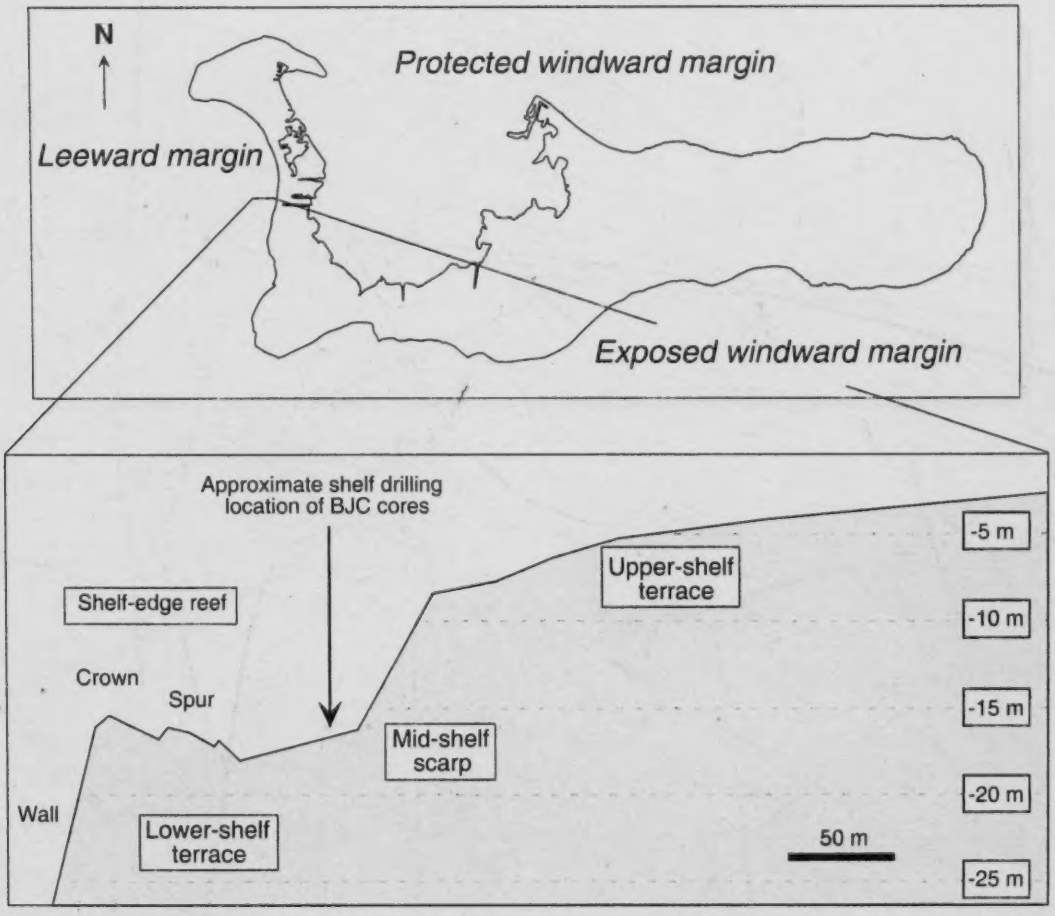

Figure 3.6. Classification of Grand Cayman margins, and simplified cross-shelf profile of Grand Cayman Island on the western leeward margin (transect W40). BJC cores were drilled from the lower-shelf terrace in water depths ~15-18 m below msl. (Modified from Blanchon, 1995; Blanchon and Jones, 1997.)

least partly obscured by skeletal sediment. A shelf-edge reef (SER) covers the outer 200 m of the lower terrace and extends down the shelf escarpment to ~75 m below msl, making a continuous circle around the island. The shelf escarpment extends from the lower-shelf terrace for 30-60 m, and plunges sub-vertically to the upper island slope at ~115-145 m below msl (Rigby and Roberts, 1976; Messing and Platt, 1987).

The upper and lower shelf terraces can be divided into a series of environments shaped by energy and light conditions (Blanchon, 1995; Blanchon and Jones, 1997). The lower terrace consists of a spur-and-sand zone which phases into SER coral buttresses and broad sediment canyons. Over the short-term, energy conditions are a result of fair weather processes. Over longer time periods, hurricanes are major factors in sediment movement, reef destruction and erosion.

The four George Town harbour cores were drilled on the lower-shelf terrace on the leeward side of the island. Seismic profiles indicate that the bedrock undulates mildly in low amplitude pinnacles beneath the sediment cover (Blanchon, 1995; Blanchon and Jones, 1997). The leeward margin has the least pronounced morphology with regard to coral pinnacles. Variation is introduced in areas that are occasionally exposed to north-west and south-west swells, but Blanchon and Jones (1997) note that "...it [the leeward shelf] is characterized by shallow low-amplitude buttresses, little spur development, and a dominance of branching corals". In the most protected areas a continuous string of corals replaces the buttresses commonly found on the other two more energetic margins. Canyons are nearly absent, except in a few locations where broad, deep sand canyons plunge between steep buttress walls. The shelf wall slopes 60-70° instead of vertically,

and flattens to the lower terrace at 15-20 m bmsl. Branching corals are common on the crown, spur and sometimes even the wall.

It is not known just how closely western Grand Cayman's marine environments of 125 ka match those of the present. Nevertheless, despite changes in paleogeography, the area west of George Town harbour would still have been the leeward side of the island during the late Pleistocene, and would have been subject to very similar water energy conditions.

3.2.1 Core BJC #1

This core is dominated by head coral floatstone with alternating branching coral floatstone. There is a discontinuity at 30 m below sea level (bsl) which was only revealed by Th/U analysis of the corals: the head corals below 30 m bsl are 104 ka, whereas the branching corals 50 cm above them are 80 ka. At this depth, the core exhibits no obvious unconformity. There is no terra rossa and/or caliche to indicate subaerial exposure, as exhibited in the Rogers Wreck Point unconformities (Vézina, 1997; Vézina *et al.*, 1999), and thin section analysis did not reveal any kind of hardground. There is a similar lack of evidence for any unconformities between 30 m bsl and 36 m bsl. Therefore, the sediments from the cores may have remained underwater during the period from ~121 ka to < 70 ka.

Acropora palmata is used as a depth indicator because monospecific communities of this coral typically grow in water depths of 5 m (Goreau and Wells, 1967). However, the *A. palmata* found at 35 m bsl is fragmented, and does not represent *in situ* growth. Therefore, water depth during deposition can only be estimated. The core's predominant

in situ corals are *Montastrea annularis* and *M. cavernosa*. The former has a bathymetric range of 0.3 to 82 m, but is commonly found at depths less than 30 m (e.g. Goreau and Wells, 1967). *M. annularis* is found in almost every coral association on the Cayman shelf (Hunter, 1994); and is therefore not a very reliable indicator of exact water depth. In BJC#1, *M. annularis* has a domal morphology, ranging from 15 to 80 cm high. At 30.5 m bsl, and 32.7 to 34 m bsl the corals are stacked vertically. Those corals may represent part of a small patch reef, or be part of a more substantial shelf edge reef. The wacke/mudstone found layered in between the head corals represents material trapped in crevasses in the reef. The presence of mud and the high degree of micritization in these layers indicate that the head corals formed in a quiet water environment. Conversely, the alternating layers of the branching coral facies represent a different set of energy conditions. The skeletal grainstone matrix contains poorly sorted, sand to gravel sized allochems that exhibit little abrasion. There is also an assortment of *Acropora cervicornis* and *Porites* sp., with fewer *Diploria* sp. and *M. annularis*: all of which are fragmented and in different stages of preservation. The skeletal sand and bioeroded fossil fragments were transported either during normal fairweather processes or during a storm. The latter is more probable, because fairweather processes would produce skeletal grains that exhibited more abrasion and better sorting. Hurricanes are the major agent of sediment transport around Grand Cayman (Blanchon, 1995).

Assuming that sea level was still at the Sangamon highstand height of 6 m above present sea-level (psl) when the 121 ka head coral grew, then the base of BJC#1 was deposited in a water depth of ~39 m bsl (Fig. 3.7). If Grand Cayman's shelf design in the late Pleistocene was similar to the present, then the 121 ka coral may have been situated

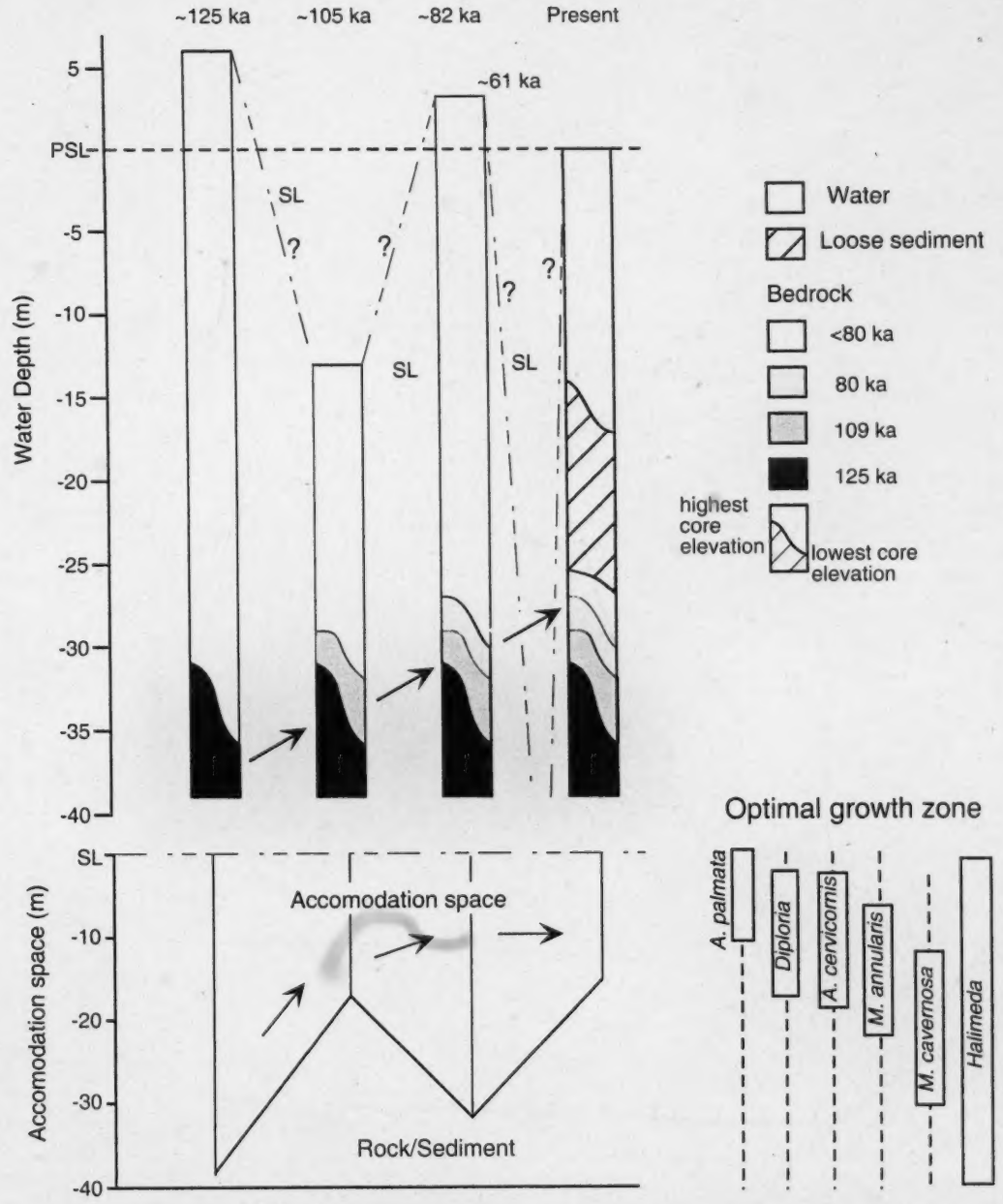

Figure 3.7. Schematic diagram showing the accumulation of preserved marine deposits over the past 130 thousand years. Information from all four cores has been amalgamated into each column. Ages are from the measured BJC core dates, and correspond to known highstand sea levels from other islands (e.g 125 ka and 105 ka Bender *et al.*, 1979; 82 ka Broecker *et al.*, 1968; 61 ka Bloom *et al.*, 1974). The sea levels marked with question marks should be treated cautiously (see Chapter 4 discussion). The lower diagram shows the accomodation space available at each highstand; the core biotas display no depth inconsistency with their known life growth zones (Humann, 1998).

on the crown of the shelf-edge reef. During the 20 m sea-level drop over the next 20 ka, the 110 ka and 104 ka head corals formed in a water depth of ~14 m bsl, hypothetically placing them on the lower-shelf terrace. The preponderance of large *in situ* head corals would place this part of the core on either the crown or base of the mid-shelf scarp.

3.2.2 Core BJC #2

This core consists predominantly of skeletal grainstone with branching coral floatstone at the base (39 m bsl) and the top (29.5 m bsl). The coral layer at the base is well-lithified and contains *Acropora cervicornis* fragments that exhibit differential preservation. Some are unaltered and nearly pristine, whereas others are coated in encrusting red algae and have leached, sediment-filled cores. Intermixed with the *A. cervicornis* are *A. palmata*, *Diploria* sp., *Montastrea annularis,* and an assortment of disarticulated but unfragmented bivalve shells that decrease in number towards the top of the interval. This mixture of differently preserved corals, unfragmented bivalves, poor cementation, and angular unsorted grainstone indicates that the interval was probably deposited under high energy conditions (i.e. storm conditions). In the middle of, and forming most of the core, is a poorly sorted, weakly cemented skeletal grainstone with medium to coarse, angular to subrounded grains (interval 30.4 m bsl to 37.6 m bsl). In the grainstone facies there is a 2 m section of missing core beginning at 31.5 m bsl. It is underlain by poorly cemented skeletal grainstone rubble (interval 33.3 to 37.6 m bsl). The missing rock was probably a more poorly cemented continuation of the skeletal grainstone. The poor sorting and lack of abrasion indicates that these grains were deposited in a low energy environment. The fragmented skeletal remains indicate that

this sediment was probably not deposited *in situ*. The lack of coral throughout most of the core indicates that this was not a reefal setting, and probably not adjacent to one. An environment prone to sediment transport and erosion would exhibit both the poor cementation and low relief of BJC#2 (compared to the other three cores).

The shallowest distinct coral layer (interval 29.7m bsl to 30.4 m bsl) contains fragmented and bored branching corals that are at least partially encrusted by other organisms (e.g. *Homotrema*), and exhibit some alteration to calcite. The poor preservation and high degree of fragmentation indicates that those fossils are not in life position, but were subject to abrasion on the seafloor for some time. The high degree of boring and encrustation indicates that they were not buried immediately.

BJC#2 does not represent an *in situ* reef. The *A. palmata* fragments are not in growth position and therefore cannot be used to estimate water depth. BJC#2 may have been part of a canyon (cf. Blanchon, 1995). Canyons channel water currents, thereby decreasing sediment residence time and minimizing rock formation within their areas. They are presently found on the west coast of Grand Cayman (Blanchon, 1995).

No dates were obtained from this core due to a dearth of unaltered coral. There is no visible evidence for any unconformities.

3.2.3 Core BJC #3

Three dates were obtained (Fig. 3.5): 135 ka, 121 ka, and 5714 years at the sediment/rock interface. Compared to BJC#1 and BJC#4, this core had the highest surface elevation at ~121 ka: there is 5 meters stratigraphic difference between the 121 ka corals found in BJC#3 and BJC#1.

There are three major beds of *Halimeda* float/rudstone, and they are 1 to 3 m thick. The *Halimeda* facies contain closely packed, well-sorted plates that have a preferred horizontal orientation. The plates also appear to be from the same species. In the upper part of the core they are preserved with little to no alteration. In contrast, those plates in parts of the core lower than 31 m bsl have been leached, and are mainly preserved as moldic porosity. The excellent, unfragmented preservation of the plates indicates that they were deposited or buried rapidly *in situ*. Blanchon (1995) and Hunter (1994) reported that *Halimeda* grow thickly over both corals and sediment on some parts of the terraces.

From 31 m to 25.7 m bsl the percentage of *Halimeda* decreases, and is replaced by a mixture of skeletal grainstone, and branching and head coral fragments similar to the storm deposits in BJC#1 and BJC #2. However, BJC#3 has a greater proportion of coral in the upper part of the section than the other two (i.e. it may be closer to a reef).

3.2.4 Core BJC #4

The bottom 9 m of this core is composed mainly of skeletal grain/wackestone and poorly preserved *Halimeda* that contains few corals. The only exception is a 2 cm thick platy *Montastrea annularis* in the bottom meter. The platy coral morphology and fine sediment denote a low energy deep water environment. The interval 31 to 34.5 m bsl is rubbly wackestone and, judging by the poor recovery, mudstone. No dates were obtained for these sections. Directly above is a 4 m thick coral-rich section. The *Acropora cervicornis* at this section's base is capped by a head coral facies that is dominated by *M.*

annularis fragments. One date, 80 ka, was obtained from a branching coral layer at 29.3 m bsl. The second, 8327 years, was found at the sediment/rock interface (25.4 m bsl).

There is an abrupt change in lithification at 30 m bsl, just below the 80 ka coral. Although there is no sharp bounding surface, this change may be indicative of an unconformity. Below, the lower rock is a poorly cemented, very fine to fine grained pack/wackestone with poor recovery. Above, there is a well-lithified coral floatstone with a medium to very coarse skeletal grainstone matrix. *A. cervicornis* is the predominant coral in the upper part of the core. A transition from deeper to shallower water would result in such a change in biota, grain size and lithification. Three small *in situ* head corals were able to establish themselves in the highest part of the core, above the dated 80 ka fossil.

3.5 Synopsis

There are five major facies in the four offshore cores: head coral floatstone, branching coral floatstone, mixed coral floatstone, *Halimeda* float/rudstone, and skeletal grain/pack/wackestone. All the core facies were deposited in deep marine environments below fairweather water processes. In places there is evidence of high energy deposition, and overall a wide variety of environments. The only evidence of unconformities rests with the coral ages obtained by Th/U analysis, and the facies change in BJC#4 at 30 m bsl. Compared to the modern shelf, and known highstand water depths, the cores were deposited on the lower terrace and the shelf-edge reef.

CHAPTER 4

ONSHORE ARCHITECTURE AND SEA LEVEL CYCLES

4.0 INTRODUCTION

Surface exposures of the Ironshore Formation, particularly on the western half of Grand Cayman, have been examined in great detail (Brunt *et al.*, 1973; Woodroffe *et al.*, 1980; Jones and Goodbody, 1984; Hunter and Jones, 1988; Jones and Pemberton, 1989; Hunter and Jones, 1989a; Hunter and Jones, 1989b; Jones and Hunter, 1990; Shourie, 1993; and Hunter and Jones, 1996). In particular, Hunter and Jones (1989b), Jones and Hunter (1990) and Shourie (1993) provided several facies classification schemes (Fig. 4.1). Variations among those schemes reflect the complexity of the succession and the fact that different studies focused on different aspects of the succession. The facies names used herein are based on those given by Jones and Hunter (1996) who summarized all previous information into one scheme (Fig. 4.2). The first part of this chapter focuses on the facies successions that are found between Vista del Mar and Morgan's Harbour, and in Paul Bodden quarries (Fig. 4.3).

Brunt *et al.* (1973) suggested that the limestones in the Ironshore Formation were deposited in a variety of reef, backreef, shoal, and lagoonal settings. Hunter and Jones (1988, 1990) fundamentally agreed with that suggestion and proposed that the Ironshore Formation was deposited in the "Ironshore Lagoon" that covered most of the western half of Grand Cayman during the Sangamon highstand, ~125,000 years BP (Fig. 4.4). This Sangamon age was based on fossils dated by Woodroffe (1983) and Emery (1981),

HUNTER AND JONES (1989B)	JONES AND HUNTER (1990)	SHOURIE (1993)
Bivalve A	Bivalve Facies	Peneroplid-Milolid Bivalve Wackstone/Packstone Facies
		Nummulitid- Bivalve Wackstone/Packstone Facies
Bivalve B		Poorly Sorted *Halimeda*- Bivalve Wackstone/Packstone Facies
		Peloidal- Bivalve Wackstone/Packstone Facies
Coral A	Coral Facies A	Coral A Floatstone/Framestone Facies
		Halimeda A-Coral Floatstone/Framestone Facies
Skeletal Grainstone	Laminated to Highly Burrowed Grainstone	Poorly Sorted Skeletal Grainstone/Packstone Facies
Coral B	Coral Facies B	Coral B Floatstone/Framestone Facies
Well Sorted Skeletal Grainstone		Well Sorted Skeletal Grainstone Facies
Moderately Burrowed Grainstone	Laminated to Highly Burrowed Grainstone	Moderately Burrowed Ooid Grainstone Facies
Highly Burrowed Grainstone		Highly Burrowed Ooid Grainstone Facies
Unidirectional Cross-bedded Grainstone	Unidirectional High-angle Cross-bedded Grainstone	Unidirectional Cross-bedded Ooid Grainstone Facies
Multidirectional Cross-bedded Grainstone	Multidirectional High-angle Cross-bedded Grainstone	Multidirectional Cross-bedded Ooid Grainstone Facies
Lithoclast Rudstone	Rudstone	Lithoclast Rudstone Facies
Bioclast Floatstone		Bioclast Floatstone Facies
Laminated Grainstone	Laminated to Low-angle Cross-bedded Grainstone	Laminated Ooid Grainstone Facies

Figure 4.1 Summary and correlation of facies names used in this chapter. (Modified from Table 2.1 in Shourie, 1993).

FACIES	LITHOTYPE	SORTING	GRAIN SIZE	SEDIMENTARY STRUCTURES	FOSSILS MAJOR	FOSSILS MINOR	TRACE FOSSILS	ENVIRON-MENT
Bivalve A	skeletal wackestone to packstone	poor	silt to very fine	Not Observed	bivalves	gastropods, foraminifera	N/O	lagoon
Bivalve B	skeletal packstone to grainstone	moderate to poor	very fine to fine	N/O	bivalves	corals, *Halimeda*, gastropods	N/O	lagoon
Coral A	coral floatstone	poor	fine to coarse	N/O	corals	bivalves, gastropods	*Gastrochaenolites* *Entobia* *Trypanites*	patch reefs
Skeletal Grainstone	skeletal grainstone	moderate	fine to coarse	moderate burrowing	none	corals, bivalves	*Polykladichnus* *Skolithos*	inter-reef
Coral B	coral boundstone	poor	fine to coarse	N/O	corals	gastropods, red algae	N/O	reef tract
Well sorted Skeletal Grainstone	skeletal grainstone	well	fine to medium	N/O	none	corals	N/O	reef channel
Moderately Burrowed Grainstone	ooid grainstone	well	fine to medium	laminated moderate burrowing	none	none	*Ophiomorpha* *Polykladichnus* *Skolithos* *Conichnus*	subtidal
Highly Burrowed Grainstone	ooid grainstone	well	fine to medium	high burrowing	none	none	*Ophiomorpha* *Polykladichnus* *Skolithos* *Planolites*	subtidal

Figure 4.2 Ironshore Formation facies classification for Grand Cayman. (Modified from Jones and Hunter, 1996, Fig. 3.)

FACIES	LITHOTYPE	SORTING	GRAIN SIZE	SEDIMENTARY STRUCTURES	FOSSILS MAJOR	FOSSILS MINOR	TRACE FOSSILS	ENVIRON-MENT
Unidirectional Cross-bedded Grainstone	ooid grainstone	well	fine to medium	unidirectional high-angle cross-bedding, low burrowing	none	none	*Polykladichnus* *Skolithos* *Conichnus* *Bergaueria* *Psilonichnus*	subtidal
Multidirectional Cross-bedded Grainstone	ooid grainstone	well	fine to medium	multidirectional high-angle cross-bedding, moderate burrowing	none	none	*Ophiomorpha* *Skolithos*	upper shoreface
Lithoclast Rudstone	lithoclast rudstone	moderate	fine to medium	high burrowing	none	none	*Ophiomorpha* *Polykladichnus* *Conichnus*	high energy subtidal
Bioclast Floatstone	bioclast floatstone	moderate	fine to medium	high-angle cross-bedding, moderate burrowing	none	corals, bivalves	*Ophiomorpha* *Polykladichnus* *Skolithos*	high energy subtidal
Laminated Grainstone	ooid grainstone	well	fine to medium	laminated to low-angle cross-bedding	none	none	none	foreshore-backshore

Figure 4.2 continued Ironshore Formation facies classification for Grand Cayman. (Modified from Jones and Hunter, 1996, Fig. 3.)

and a wave-cut notch +6 m asl that is found near Rogers Wreck Point on the northeast coast of Grand Cayman. That notch is consistent with estimates of the Sangamon highstand from the Yucatan Peninsula (Szabo *et al.*, 1978), Haiti (Dodge *et al.*, 1983), Bahamas (Neumann and Moore, 1975), and Jamaica (Boss and Liddell, 1987).

4.1 Stratigraphy

Surface exposures of the Ironshore Formation on the western part of Grand Cayman belong to depositional units D and F (Fig. 2.5) that are separated from each other by an erosional surface. Between Vista Del Mar and Morgan's Harbour that erosional surface is characterized by relief of up to 2.3 m and commonly has large tabular lithoclasts (cf. Jones and Pemberton, 1989) lying on its surface (Figs. 4.5, 4.6). Unit D, which lies under the erosional surface, consists of patch reef facies (Coral A and Coral B) and oolitic inter-patch reef facies (Jones and Pemberton, 1989). Corals from patch reefs at Vista Del Mar, Canary Lane Quarry and Morgan's Harbour were dated at 136 +/- 3.5 ka (~ 1 m asl), 133 +/- 3.5 ka (~ 2.5 m asl), and 123 +/- 3 ka (~ 1 m asl), respectively. These are comparable in age to corals that have been dated from Paul Bodden Quarry A (136 +/- 3.5 ka, ~1.5 m asl), Jackson's Pond (147 +/- 4 ka) and a coral obtained 3 m below sea level in well TUF #1 (143 +/- 3 ka) (Fig. 2.5). This unit, which ranges from at least 3 m bsl to 2 m asl, contains dated material comparable in age to unit D as defined by Vézina (1997) and Vézina *et al.* (1999). When plotted against the SPECMAP oxygen isotope curve (Fig. 4.7) the coral ages cluster at the beginning of the transgressive rise to substage 5e and the Sangamon highstand.

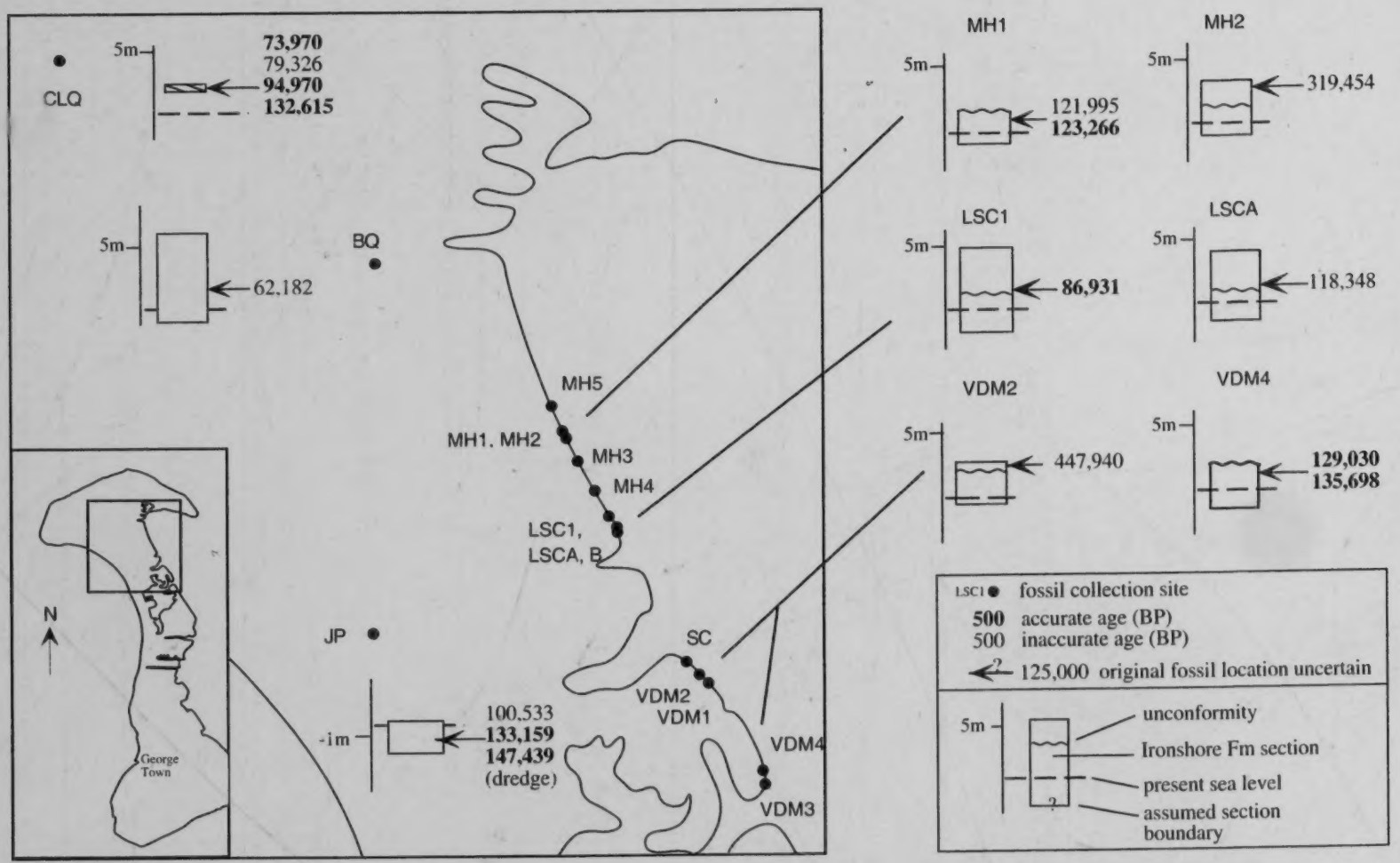

Figure 4.3. Site locations and fossil ages (where applicable) of the VDM-SC-LSC-MH-BQG-CLQ transect, Grand Cayman.

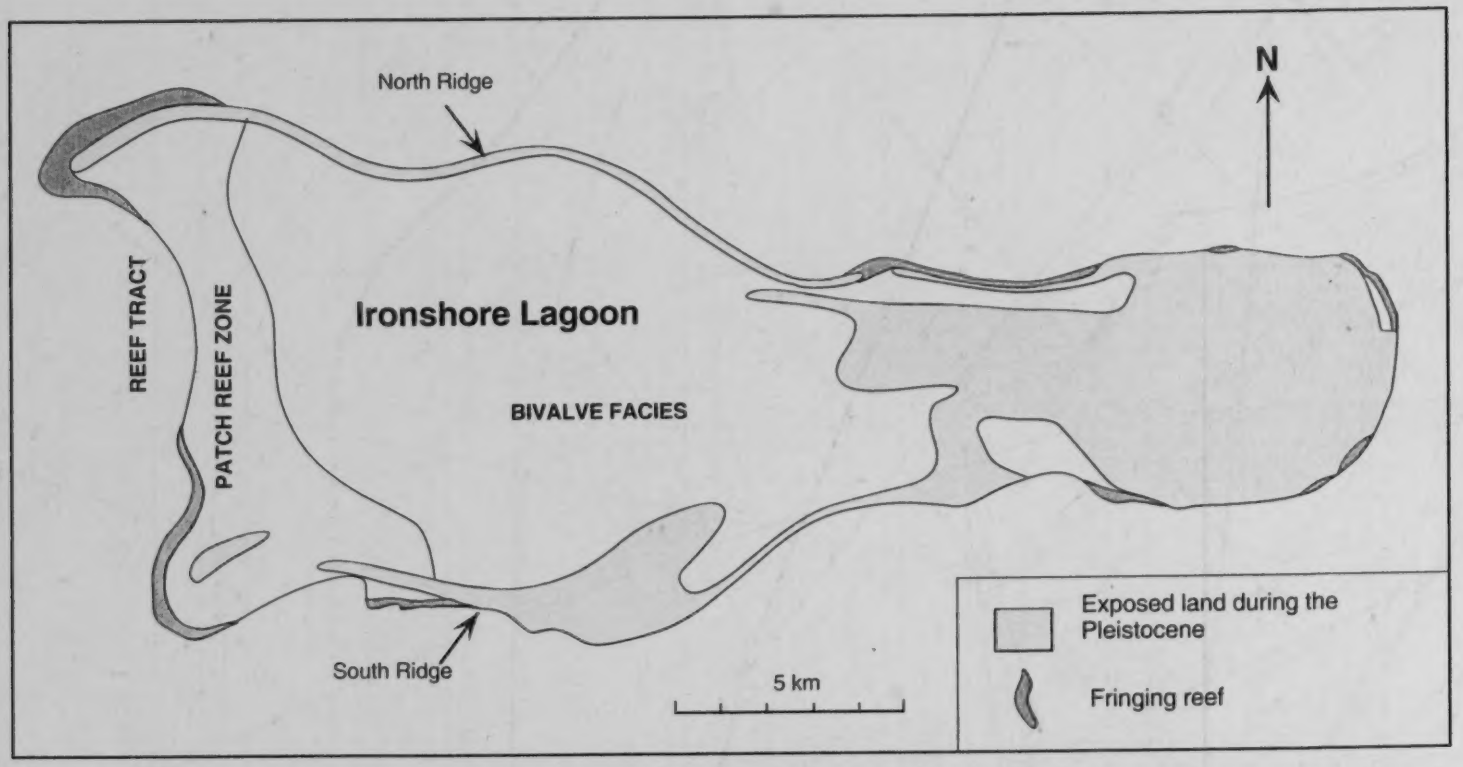

Figure 4.4. Paleogeographic map for Grand Cayman during the Late Pleistocene when sea level was 6 m above present day sea level. This is the depositional framework in which the sediments of the Ironshore Formation accumulated. Modified from Hunter and Jones (1988) and Jones and Hunter (1990, fig. 2).

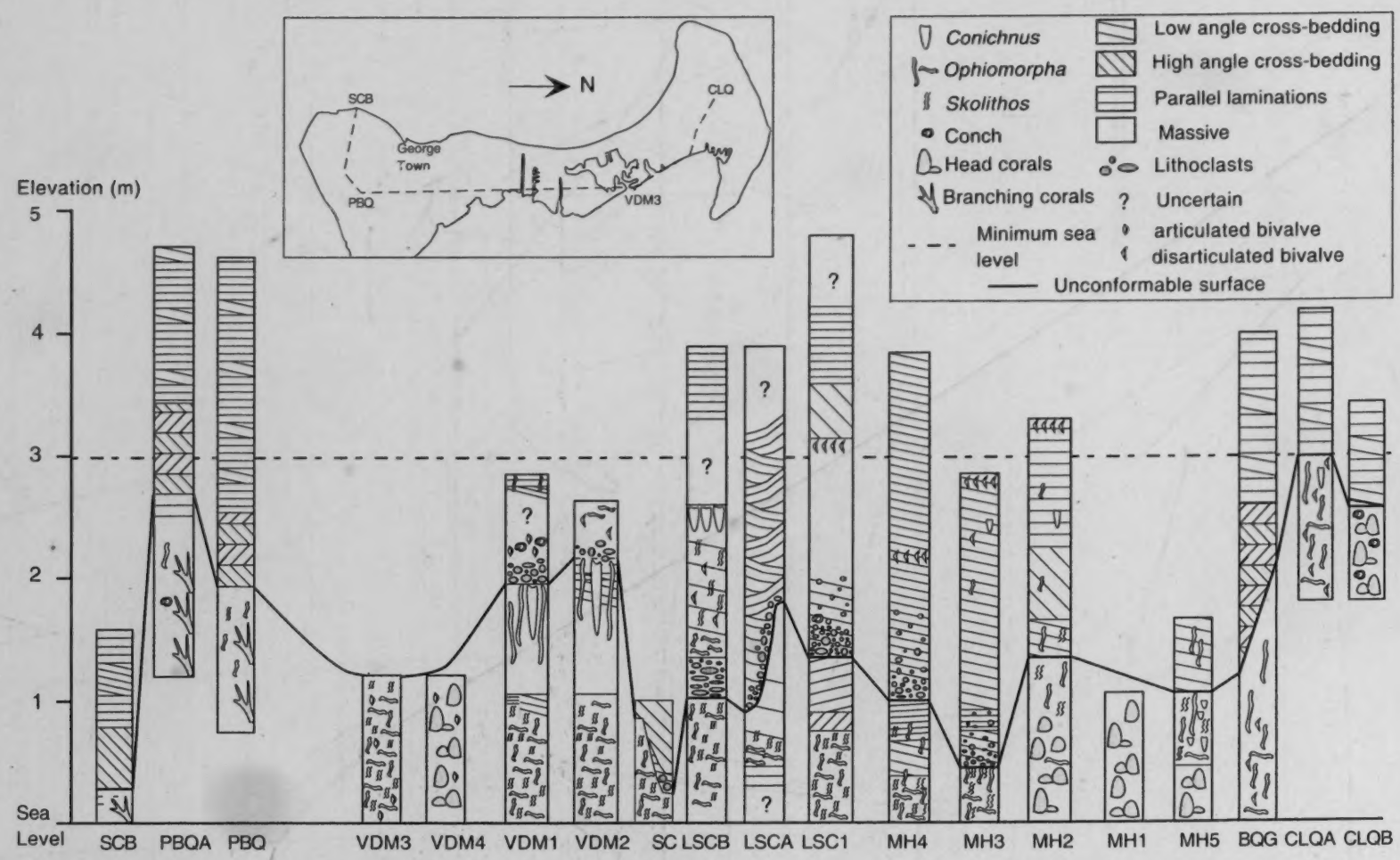

Figure 4.5 Cross-section of transect SCB-PBQ-VDM-LSC-MH-BQG-CLQ through the Ironshore Formation. Portions marked uncertain were either badly eroded, or inaccessible due to vegetation or location. Not to horizontal scale. Minimum sea level based on the highest occurence of *Conichnus*.

The erosional discontinuity is well exposed along the western shore of North Sound between Vista del Mar and Morgan's Harbour (Fig. 4.6). Tabular lithoclasts, up to 0.22 m x 0.21 m x 0.03 m (Appendix C), lie on the erosional surface, and the moderate angle cross-bedded ooid grainstones deposited above them contrast sharply with the patch reef/inter-patch reef facies found below the discontinuity. Although devoid of corals, this upper unit contains numerous bivalves but only scattered conchs. Dates derived from the conchs were 87 +/- 3 ka (Little Salt Creek, ~ 2 m asl), 98 +/- 3 ka (Paul Bodden Quarry A, ~ 2 m asl), and 87 +/- 6 ka (Paul Bodden Quarry, 1-2 m asl). Three conchs, obtained from coral-free laminar to high angle cross-bedded ooid grainstones at Canary Lane Quarry, yielded dates of 74 +/- 1 ka, 79 +/- 2 ka, and 95 +/- 3 ka. On the SPECMAP oxygen isotope curve (Fig. 4.7) the younger ages (73 ka to 87 ka) plot on both the transgressive and regressive slopes of substage 5a, and are hereby assigned to Unit F. The unit has an average age of ~80 ka. The two older dates, 95 ka and 98 ka fall on the highstand peak of substage 5c, and are tentatively assigned to Unit E.

Unit F is formed primarily of high-angle, cross-bedded ooid grainstones whereas the upper part is formed of planer laminated ooid grainstones (Fig. 4.5). The tabular lithoclasts found on the erosional discontinuity (Fig. 4.6) have been interpreted as channel lag formed by the break-up of previously lithified or partially lithified rock (Jones and Pemberton, 1989). Alternately, the lithoclasts may have originated as a storm wash deposit. Certainly, hurricanes have been responsible for the movement of much larger boulders on Grand Cayman (Jones and Hunter, 1992). Whether or not Unit F was deposited under hurricane conditions or in a tidal channel setting (or both) is unclear,

partly due to the disruption of lamination and bedding by bioturbation, or weathering in some parts of the outcrops.

The unbioturbated high angle cross-bedded ooid grainstones of Unit F at Salt Creek formed under unidirectional high energy conditions away from reef environments: they lack fossil material; they apparently dip to the northeast; and the discontinuity underlying them has the lowest stratigraphic relief of the entire Vista del Mar/Morgan's Harbour transect (Fig. 4.5). The origin of the overlying and laterally adjacent cross-bedded ooid and planar bedded grainstones is open to debate. The low angle to planar laminations were formed in lower energy conditions than the high angle laminations, and the bedding dip angles alternate at several localities (Fig. 4.5, e.g. PBQ, PBQA, LSCA, BQG), indicating tidal influences. There is no way to determine how much reworking these parts of Unit F have undergone.

The lack of corals suggests that the depositional environment was not conducive to normal marine biotas. The cross-bedded ooid grainstones are, however, penetrated by numerous trace fossils (e.g. Pemberton and Jones, 1988; Jones and Pemberton, 1989) that include *Conichnus*, whose formation is attributed to sea anemones, and *Ophiomorpha*, which is attributed to the burrowing ghost shrimp. The presence of these trace fossils in the lower 2.5 to 3 m of Unit F indicates that subtidal deposition must have been responsible for the formation of that part of the succession.

A conch obtained from locality MAQ, located on the south-central coast of Grand Cayman (Fig. 2.6) yielded an age, 108 +/- 3 ka. This correlates with unit E, which is present in the offshore succession (Figs. 2.3, 4.6). Additional evidence has been found at CLQ and PBQA (see above), but these fossils were found loose and their exact

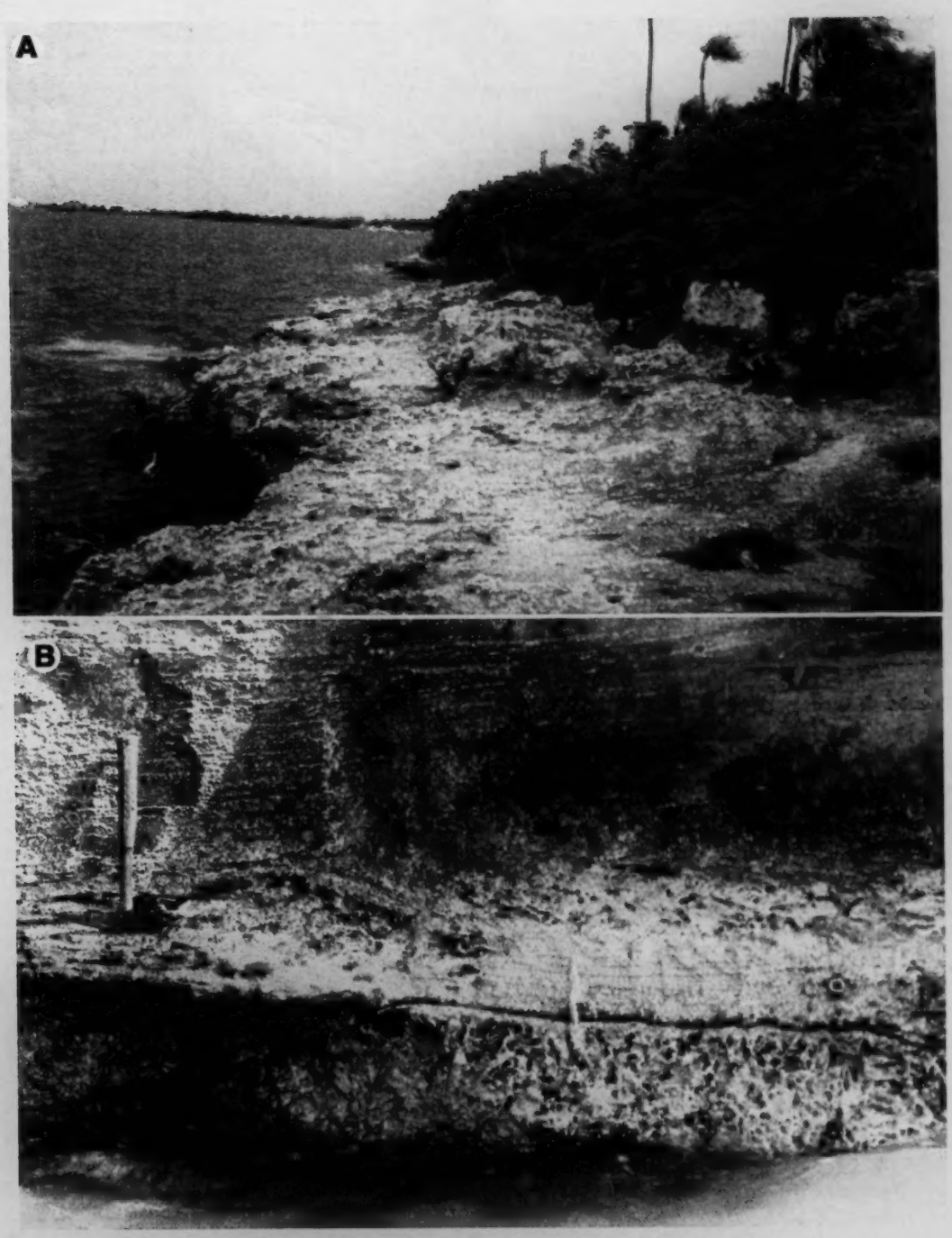

Figure 4.6. (A) Discontinuity surface between units D and F, view to south, west coast of North Sound just north of Little Salt Creek. (B) Discontinuity separating units D and F. Outcrop on west coast of North Sound, near Salt Creek. Hammer is 0.3 m long.

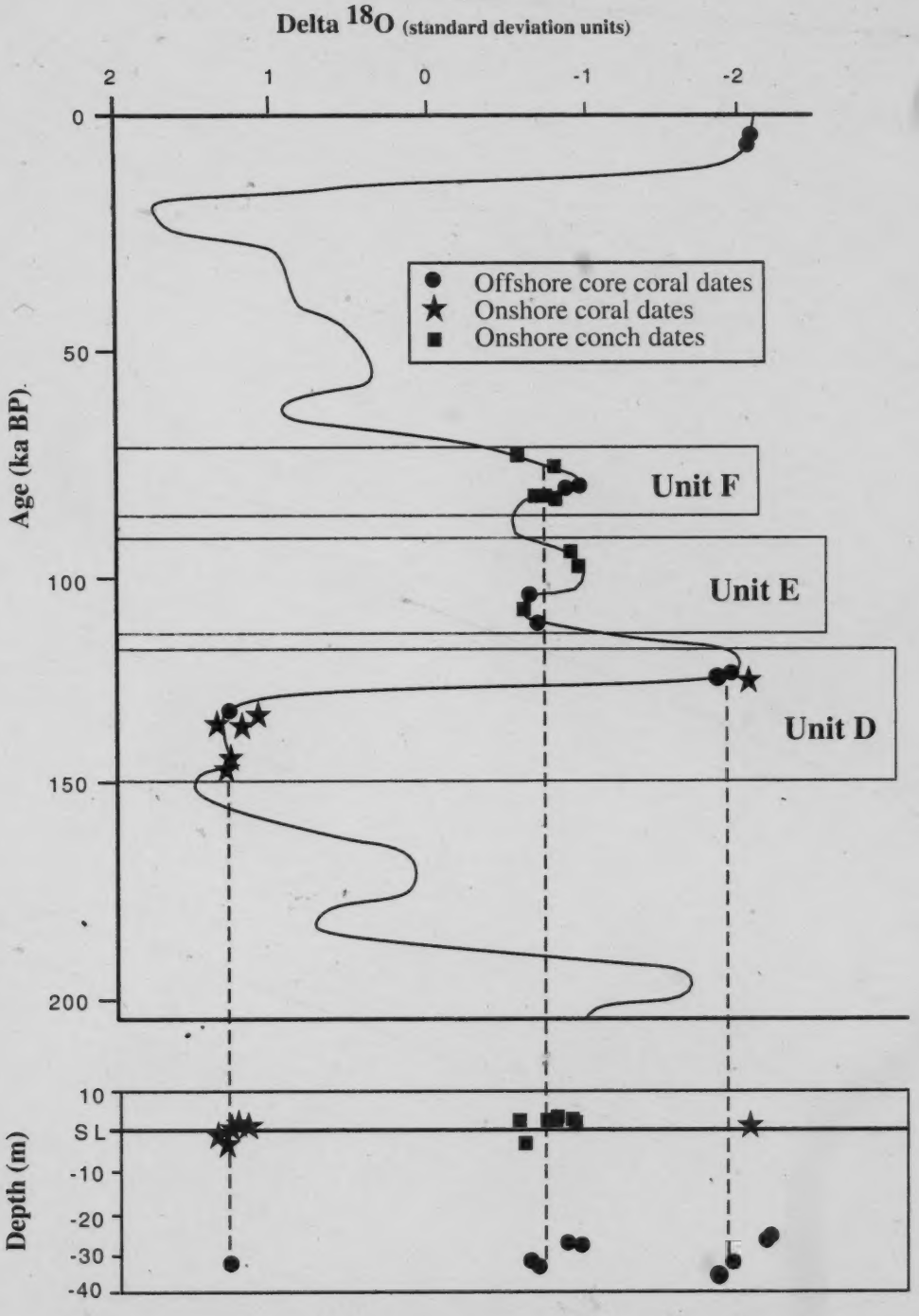

Figure 4.7 Valid fossil dates (this study) superinposed on the oxygen isotope SPECMAP (modified from Imbrie *et al.*, 1984; Vezina, 1997; and Vezina *et al.*, 1999). Negative peaks indicate sea level highstands. Depths are measured in meters above and below present sea level.

stratigraphic position is therefore unknown. No comparable ages were found in the VDM-MH transect succession that is exposed in surface exposures on the western part of Grand Cayman. It is possible that deposits of that age were removed by the erosional episode that led to the formation of the discontinuity that separates units D and F in the area between Vista del Mar and Morgan's Harbour.

Unit D is the oldest unit that crops out on the western part of Grand Cayman. Its fossil ages encompass those in the Unit D section that Vézina (1997) and Vézina *et al.* (1999) described from the northeast part of Grand Cayman, and the Unit D that is found in the offshore cores. The disconformity exposed in the outcrops between Vista del Mar and Morgan's Harbour represents a time gap of 35 to 45 ka and should therefore be treated as an unconformity. Unit F formed ~ 80 ka, and can be correlated to the offshore cores. It should be noted that Units D, E, and F correlate to sea level transgressions, regressions, and highstands associated with substages 5e, 5c and 5a (Fig. 4.7).

4.2 Paleogeography and Sea Level

The placement of fossil ages on the SPECMAP oxygen isotope sea level curve reveals some inconsistencies between this study's data and attributed sea level positions from other parts of the world. For example, the amplitude of sea level change between the 18 ka lowstand and the present day highstand has been interpreted as 130 m, based on an undated submerged terrace on the Huon Peninsula, New Guinea (Chappell and Shackleton, 1986). As plotted on the oxygen isotope sea level curve, this transgression is roughly equivalent in amplitude to the Sangamon transgression. Hence, the sea level difference between stages 6 and 5e may also be 130 m. Aharon and Chappell (1986)

suggested, on the basis of evidence from New Guinea, that the 5a highstand at 85 ka was associated with a –19 m sea level. However, the fossil data from Grand Cayman demonstrate two contradictions to these values. First, the 135 ka to 147 ka coral dates correspond to the beginning of the transgression preceding the Sangamon, yet they are found at depths of 31 m bsl to 1 m asl, not the expected 130 m bsl values associated with the Huon Peninsula (Chappell and Shackleton, 1986). Second, the stratigraphic position of the cross-bedded ooid grainstones and *Conichnus* in the VDM-MH transect (Fig. 4.5) indicates that the material was deposited in a shallow marine environment at least 3 m above present day sea level. Conchs taken from just below the occurrences of *Conichnus* correspond in age to substage 5a. However, the sea level position suggested by the Grand Cayman data is anomalous compared to other estimates of the 5a highstand position that have been derived from various Caribbean and Pacific islands (Table 4.1),

Table 4.1 Comparison of 5a highstand sea level estimates.

Place	Age (ka)	Estimated sea level (compared to psl)	Reference
Barbados	82		Bender *et al.*, 1979
	82	~ -14 m	Broecker *et al.*, 1968
	82	~ - 15 m	Matthews, 1973
San Salvador	~ 85	< -2 m	Carew & Mylroie, 1987
Haiti	81	- 13 m	Dodge *et al.*, 1983
Huon Peninsula New Guinea	85		Aharon, 1983
	85	-16 to – 30 m	Bloom *et al.*, 1974
Bahamas	97-100	- 10 to - 15 m	Li *et al.*, 1989
U.S. Atlantic Plain	94	6.5 +/- 3.5 m	Cronin *et al.*, 1981
	72	7 +/- 3 m	Cronin *et al.*, 1981

and the –19 m sea level proposed by Aharon and Chappell (1986) from Huon Peninsula data.

There are several possible explanations for these inconsistencies.

- Grand Cayman (and therefore its fossils) may have been subjected to tectonic uplift, thereby placing fossils above their original deposited stratigraphic positions. However, Grand Cayman appears to have been stable for at least the last 125,000 years (cf. Jones and Hunter, 1990). This suggestion is supported by the presence of a wave-cut notch, 6 m above present day sea level, on the northeast coast of Grand Cayman. This is the same elevation as the Sangamon wave-cut notch found on other islands such as Bermuda (Harmon *et al.*, 1981). Thus, it is reasonable to assume that Grand Cayman has not undergone significant uplift or tilting in the past 200 ka at least, and that Units D, E, and F are stratigraphically at the same height as when they were deposited.
- The onshore evidence for Unit F is entirely based on dates from conchs. It is possible that these fossils are less reliable than corals (see the fossil type evaluation in chapter 2 for more detail), and that their Th/U ages actually may be younger than their true ages. The remaining Unit F ages were gained from offshore core corals at depths of -27 m (Fig. 4.7), which would be consistent with the -19 m 5a highstand (Aharon and Chappell, 1986). Further investigation requires more fossil collecting and dating from Unit F, specifically for corals. Ideally, a comparison of the Th/U ages from corals and conchs collected at the same stratigraphic position and location would allow a researcher to determine

any anomalies between the respective age results. Unfortunately, one of the field collection problems was the dearth of coral in Unit F deposits.

- The coral ages reveal an interesting relationship between sea level and age. Five onshore corals and one offshore coral cluster in the lowstand preceding substage 5e (Fig. 4.7). Their ages range from 147 +/- 4 ka to 133 +/- 3.5 ka. Even at the limits of their age errors, they still grew at the beginning of the transgression. Compared to the -130 m sea level position used by proxy from 18 ka data (Chappell and Shackleton, 1986), these corals were deposited in depths ranging from –32 m to +1 m psl. Even using the –32m depth as a sea level minimum, this is a significant difference from –130 m.
- Much of the information on substage 5a is based on evidence from Barbados and New Guinea, both of which are unstable islands undergoing uplift. Estimates of the highstand positions from these islands incorporate numerous assumptions regarding the rate of uplift of each island, and assume that uplift was constant through time. Thus, any highstand position obtained from these calculations should be treated with some caution. Additionally, Chappell and Shackleton (1986), in their evaluation of the 18 ka -130 m lowstand determined from the Huon Peninsula, warned that variations in global sea level positions should be expected in light of changing ocean and ice volumes. Estimates for the 5a highstand from San Salvador and the U.S. coastal plain (Virginia, North and South Carolina) are close to those derived from Grand Cayman (Table 4.1).

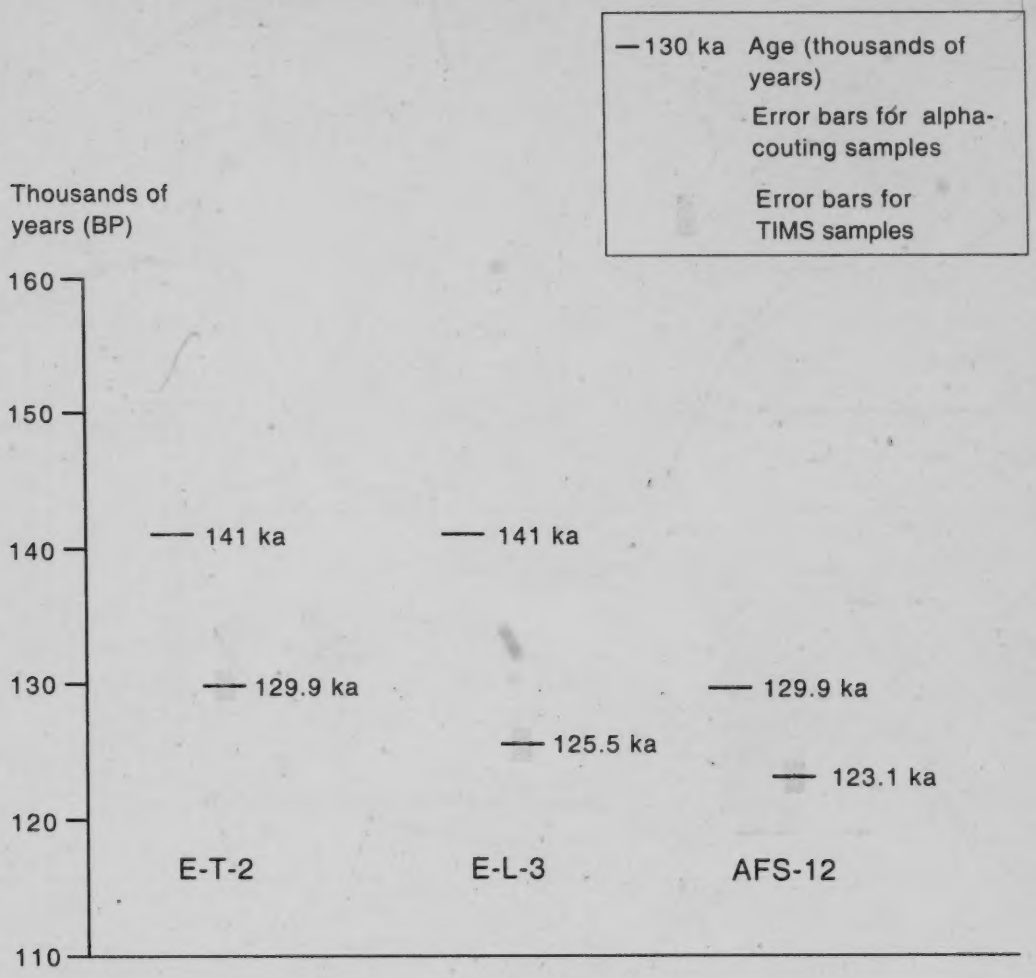

Figure 4.8 Graph comparing the Th/U ages of three fossil corals, AFS-12, E-T-2, and E-L-3 (data from Edwards *et al.*, 1986, table 5; E-T-2 and E-L-3 alpha ages from Ku, unpublished; AFS-12 alpha ages from Bloom et al., 1978). Each coral was dated by two techniques, thermal ion mass spectroscopy (TIMS) and alpha-counting. All errors are 2 sigma. Sample AFS-12 represents an average age of three subsamples. Note that the alpha-counting ages are all older, and have considerably more error than the TIMS ages.

It should also be mentioned that many of the dates used for determining sea levels on other Caribbean islands relied on Th/U dates derived by an alpha-counting technique that produces a higher error margin than the TIMS technique (used for this study), which was developed in the late 1980's. A comparison of the results obtained using the two different techniques on the same samples demonstrates the significantly greater accuracy obtained using TIMS (Fig. 4.8). In general, the TIMS results are younger, although within the error margin of the alpha-counting age. The age difference between techniques ranged from 7 to 16 ka. Therefore, dates derived by the alpha-counting technique should be treated with some caution.

4.3 Synopsis

The Ironshore Formation that crops out on Grand Cayman contains three units that correspond to transgressive and regressive cycles on the oxygen isotope sea level curve. Using both onshore and offshore fossil data (Tables 2.3 and 2.4), Unit D ranges in age from 123 ka to 147 ka (average age of 133 ka), predominantly at the beginning of the transgression of the Sangamon highstand. Unit E ranges in age from 95 ka to 110 ka (average age of 101 ka), and was deposited in part at the beginning of the transgression preceding substage 5c, and just after the 5c highstand. Unit F ranges in age from 80 ka to 87 ka (average age of 80 ka) and was deposited throughout the transgressive and regressive cycles of substage 5a.

Further investigation is required to eliminate inconsistencies between the minimum sea level positions derived from this study's data, and the established sea level record.

CHAPTER FIVE

CONCLUSIONS

Detailed study of the Pleistocene succession found in offshore cores and cropping out on Grand Cayman has yielded the following important conclusions.

1. The Ironshore Formation on Grand Cayman Island, originally treated as a single unit, can be divided into units A, B, C, D (Vezina,1997; Vézina *et al.*, 1999), E and F (this study).
2. As shown by Vézina (1997) and Vézina *et al.* (1999), units A to D possibly developed during highstands at >400<<1500 ka, 346 ka, 229 ka, and 131 ka.
3. According to this study, Unit D was deposited between 147 ka and 123 ka, during the transgressive cycle of substage 5e. Units E and F developed in association with transgressive and regressive cycles from 95 ka to 110 ka (substage 5c), and 80 ka to 87 ka (substage 5a), respectively.
4. Further investigation is needed with regard to sea level positions indicated by this study's data, and the established oxygen isotope/sea level record data. Corals grown between 134 and 147 ka indicate a transgressive sea level position of –31 m to +1 m.
5. In outcrops along the west coast of North Sound, Units E and F are separated by an erosional unconformity. It has a maximum of relief of 2.3 m and represents a time gap of 35,000 to 45,000 years.

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APPENDIX A

Site names, Abbreviations and Locations

The BJC core locations were measured by surveyor Mike Whiteman (Lands and Survey Department) in October 1996, and printed in the Moffat & Nichol International "Report on Geotechnical Investigation Program". The remaining site measurements were obtained during November 1999 and February 2001 fieldwork. Locations marked with an asterisk were calculated from a 1:25,00 map of Grand Cayman. Two sampling site locations (indicated by double asterisks) could not be accurately determined due to discrepancies between old maps and the present altered landscape. Thus the latitude and longitude of these sites are estimates. Brian Jones obtained the remaining location readings using a hand-held GPS recorder.

NAME	ABBREVIATION	LATITUDE	LONGITUDE
Brian Jones Core #1	BJC#1	19° 17' 58.0"	81° 23' 17.4"
Brian Jones Core #2	BJC#2	19° 18' 13.2"	81° 23' 24.0"
Brian Jones Core #3	BJC#3	19° 18' 29.7"	81° 23' 33.9"
Brian Jones Core #4	BJC#4	19° 17' 37.8"	81° 23' 22.2"
Boat Launch	BL	19° 22' 38.4"	81° 25' 10.4"
Botabano Quarry*	BQ	19° 22' 48.9"	81° 23' 14.0"
Canary Lane Quarry*	CLQ	19° 23' 07.9"	81° 24' 04.7"
Jackson's Pond	JP	19° 21' 52.9"	81° 23' 19.6"
Little Salt Creek	LSC	19° 22' 07.4"	81° 22' 37.5"
Little Salt Creek A	LSCA	19° 22' 05.5"	81° 22' 34.6"
Little Salt Creek B	LSCB	19° 22' 05.2"	81° 22' 34.7"

NAME	ABBREVIATION	LATITUDE	LONGITUDE
Midlands Acres Quarry	MAQ	19° 18' 22.6"	81° 13' 06.0"
Morgan's Harbour	MH1	19° 22' 16.2"	81° 22' 43.6"
	MH2	19° 22' 15.8"	81° 22' 44.5"
	MH3	19° 22' 13.0"	81° 22' 40.6"
	MH4	19° 22' 06.8"	81° 22' 38.2"
	MH5	19° 22' 19.5"	81° 22' 42.2"
Newlands, Sunset Landing**	NSL	19° 17' 51.4"	81° 18' 31.2"
Omega Gardens	OG	19° 17' 39.3"	81° 19' 48.5"
Paul Bodden's Quarry	PBQ	19° 16' 57.0"	81° 22' 30.6"
Paul Bodden's Quarry A	PBQA	19° 16' 36.8"	81° 22' 43.5"
Rogers Wreck Point*	RWP	19° 21' 11.4"	81° 05' 49.1"
Salt Creek	SC	19° 21' 47.7"	81° 22' 26.7"
Smith's Cove Barcadere	SCB	19° 16' 35.5"	81° 23' 31.6"
Tarpon Springs Estate**	TSE	19° 18' 18.3"	81° 12' 21.4"
Turtle Farm*	TF	19° 22' 52.3"	81° 25' 05.2"
Vista Del Mar	VDM1	19° 21' 43.9"	81° 22' 24.3"
	VDM2	19° 21' 44.5"	81° 22' 23.8"
	VDM3	19° 21' 28.1"	81° 22' 12.5"
	VDM4	19° 21' 29.3"	81° 22' 14'

APPENDIX B

OFFSHORE CORE POROSITY & PERMEABILITY TEST RESULTS

These are the porosity and permeability results of seven core samples taken from offshore cores 1 and 3. The testing was done by the Core Laboratory, Calgary, Alberta, Canada.

Core	**Depth** (ft)	**Permeability**			**Porosity** (%)	**Grain Density** (gm/cc)	**Bulk Density** (gm/cc)
		Max. K_{air} md	*90 degree* K_{air} md	*Vertical* K_{air} md			
3	68.0	895	844.	462	40.0	2.60	1.56
3	32.0	187	69.3	182	18.1	2.70	2.21
3	33.5	10240	3010	399	19.9	2.67	2.14
3	27.3	254	211	25.6	19.1	2.72	2.20
1	56.0	2060	2440	1060	36.2	2.71	1.73
1	72.5	542	248	34.2	24.7	2.76	2.08
1	40.4	5510	5200	2440	29.8	2.70	1.90

APPENDIX C

LITHOCLAST DIMENSIONS

Lithoclasts from the Unit D/Unit F unconformity were sampled at Little Salt Creek. A ruler was used to measure length, width, and where applicable, height, for lithoclasts within a 0.5 m radius section. Each row represents two lithoclasts, the first measured in all three dimensions, the second in only two. The average for each dimension category is listed in bold at the bottom of the table.

Length (cm)	Width (cm)	Height (cm)	Length (cm)	Width (cm)
11	8	2	5.5	7
4	2.5	--	8	4
6.5	6.5	--	4	2.5
2	2.5	1	2.5	2
6	3.5	2.5	3	4
11	9	4	6	5.5
7	4	3	3.5	4
22	21	3	4	2
4	3	1.5	2	1
1.5	2.5	2	5.5	4
4	4.5	2.5	8	5
9	5	4	9	8
8	6	2	7	5
4	5	2.5	2.5	3
3	3	3	8	4.5
3	3	2	12	8

Length (cm)		Width (cm)	Height (cm)	Length (cm)	Width (cm)
18		8	7	2	3
19		5	4	8	5
20		14	7	4	2.5
4		3	1	4	4
4		3	1	4	1
5		3	3	2.5	1
Avg.	**8**	**5.7**	**2.6**	**5.2**	**3.9**

APPENDIX D

Offshore Core Logs

Note: All cores are comprised of limestone. Thin section samples are prefixed with **MC99**, porosity and permeability tests with **PP-**.

Components

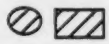
Porites sp.

Acropora palmata

Acropora cervicornis

Diploria sp.

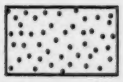
Montastrea cavernosa

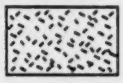

Montastrea annularis

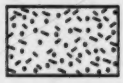
Gastropod

Bivalve

Rock Types

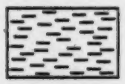

Skeletal grainstone

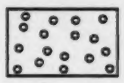

Skeletal wackestone


Skeletal packstone

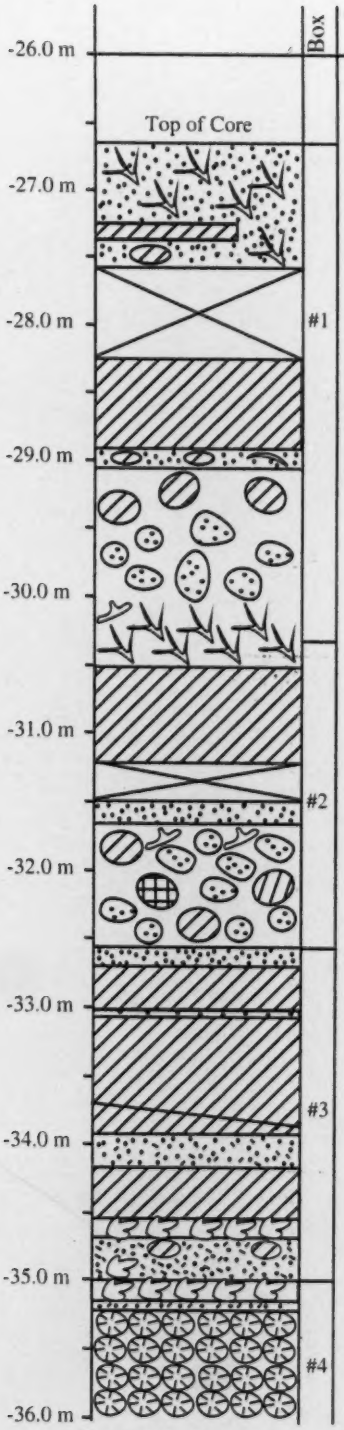
Rubble (due to poor recovery)

No core


Halimeda float/rudstone


Rudstone

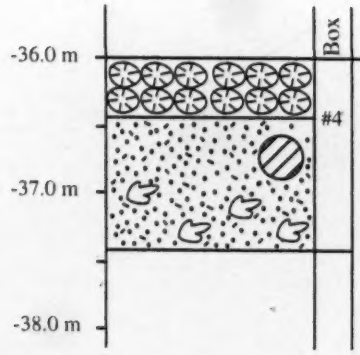
CORE BJC#1



Description

- -26.7 to -27.6 m: Poorly sorted, medium to coarse, sub-angular to sub-rounded skeletal grainstone matrix. Lithified, more friable from -27.0 to 27.25 m. Disarticulated bivalves, gastropods (including 4 cm long conch piece), *Homotrema*, benthic forams, mm scale *Halimeda* fragments present. 2-3 cm diameter *A. cervicornis* branches; some well-preserved, some lithified, coated in encrusting red algae and extesively bored. Some of these borings are filled with reddish sediment. Shells generally unbroken; retain original colouring. **PP 1-40.4**
- -27.3 m: Bored *Montastrea annularis* pieces overlie a 5 cm layer of 0.5-1.5 cm diameter *A. cervicornis* fragments.
- *M. annularis* head. Excellent preservation. No matrix.
- Skeletal grainstone with *M. annularis*, benthic forams, bivalve and gastropod fragments. **MC99-1-48.2, MC99-1-48.6, MC99-1-48.8.**
- -29.2 m to -30.5 m: Poor (~40%) recovery. Upper 20 cm of interval contains *M. annularis*.
- -30.1 to -30.5 m: Well preserved *A. cervicornis* sticks 2-5 cm long, 0.5-1 cm diameter; most encrusted with red algae and bored. One *Agaricia* 2 cm long.
- Two pieces well-preserved *M. annularis*; top piece=15 cm long and capped by 1 cm encrusting red algae, lower=45 cm long. Pieces split by 2 cm thick layer of skeletal grainstone and ~1 cm long *A. cervicornis* pieces.
- **PP 1-61**
- -31.7 to -32.6 m: Rubble. Well-preserved 1-6 cm long coral pieces (*Porites*, *Diploria clivosa*, *Agaricia fragilis*[?], *M. annularis)* in skeletal pack/wackestone matrix. Poor recovery: 60 cm of core recovered over 90 cm interval. Bivalve borings in coral.
- -32.6 to -32.7 m: Unbroken molluscs, 0.5 cm dia. intraclasts, 1 cm pieces of *M. annularis*. Skeletal grainstone matrix.
- -32.7 to -33 m: Well-preserved *M. annularis*. Sediment-filled borings in top 3-5 cm of coral head. *A. palmata* at -33.05 m.
- Well-preserved *M. annularis* head for entire length and diameter of core. Some 0.5-1.5 cm long boring bivalves. Capped by encrusting coral (*Agaricia*?) 2 cm thick. Diagonal break in lower 1/3 of core that contains 2 cm thick layer of well-lithified skeletal wackestone with *Halimeda* fragments and echinoid spines.
- -33.9 to -34.2 m: Well-lithified but porous. Lower half more friable. Alternating skeletal grainstone and greyish white wacke/mudstone matrix. Mud contains minor horizontal burrows (~0.5 cm diameter).
- -34.7 to -35 m: Small pieces of *M. annularis*, 8 cm long *A. palmata*, in pack/wackestone matrix with grey/white mud pockets. First appearance of *Halimeda* plates at -34.9 m.
- -35.2 m: Well-lithified, porous skeletal packstone. *Halimeda* plates.
- Well-preserved *Montastrea cavernosa* colony to 36.45m. Bivalve boring 2 cm long in upper 5 cm.

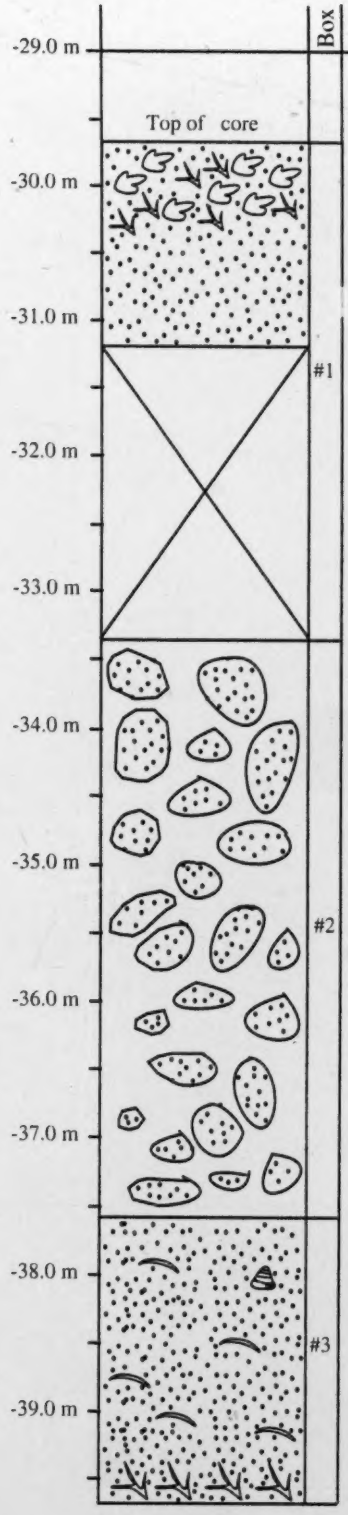
CORE BJC#1



Description

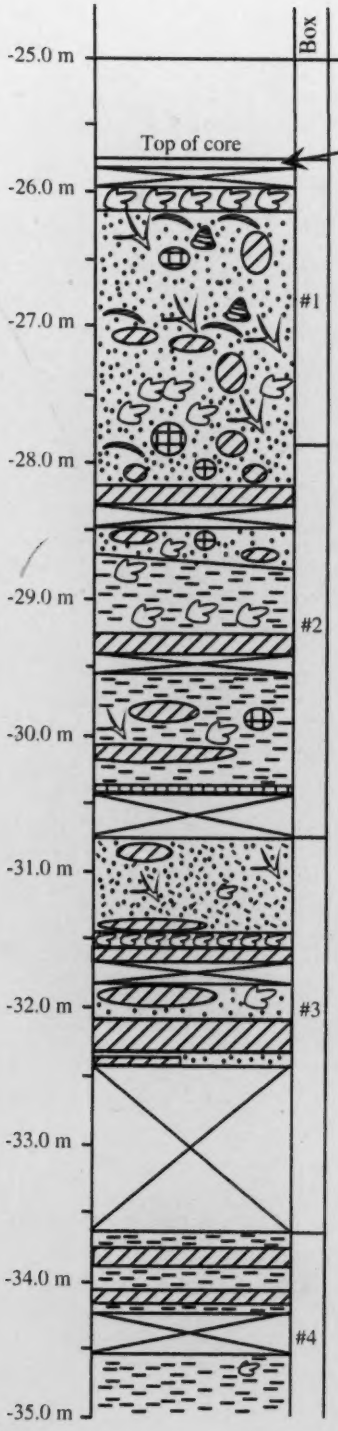
- 1 cm thick break at -36.0 m; contains skeletal grainstone matrix with serpulids and forams.
- **PP 1-72.5, MC-1-73.8, MC-1-74**
- *M. annularis* colony with bivalve borings.
- -36.4 to -37.4 m: Skeletal grainstone to packstone, well-lithified and porous. Very fine to fine skeletal grains, mainly unrecogizable. *A. palmata* patches are light brown. Cm scale patches of grey/white mud -37.4 m.

CORE BJC#2



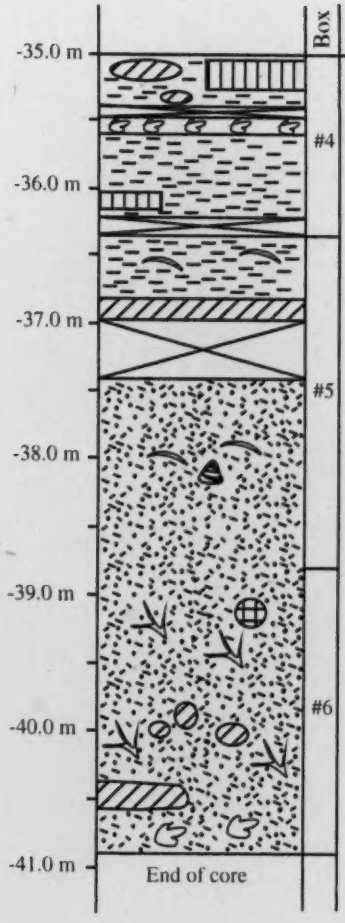
- -29.7 to -30.4 m : Poorly-preserved 2-4 cm long *A. palmata,* and well-lithified 1-2 cm diameter *A. cervicornis* pieces. One *Porites porites* 1 cm long. *Homotrema* encrusts some *A. cervicornis* surfaces. Skeletal grainstone matrix with medium to very coarse, very well lithified grains, including shell and *Halimeda* fragments, red algae, unidentified particles, composite grains, and three 1.5 cm long purple echinoid spines (*Diadema*?).
- -30.4 to 33.33m: Very fine to coarse, predominantly medium to coarse, sub-angular to sub-rounded skeletal grainstone. Contents same as above.
- -33.4 to -37.6 m: Rubbly cream-coloured skeletal grainstone with 50% recovery. Poorly lithified, friable. Grain size predominantly medium to coarse, with subtle overall coarsening from -34.5 to -37.6 m. Very fine to medium grain size in -33.4 to -34.5 m. Grains are poorly sorted, angular to sub-angular to sub-rounded. No mud, sedimentary structures, bioturbation or ooids. Grains include red algae, benthic forams shell fragments and unidentified particles. Slight reddish tinge to rocks -33.4 to -33.5 m.
- -37.6 to -39.7 m: Similar to contents of box #2, but better lithification. Scattered, disarticulated, unfragmented bivalves throughout box #3, increasing in number with depth. Grains include echinoid spines, red algae, serpulids, whole gastropod (2 cm), unidentified particles.
- Basal 23 cm contains 0.5 to 1 cm diameter *A. cervicornis* fragments with differential preservation--some are coated in encrusting red algae with leached and sediment-filled cores, some are very well-preserved. Some coral surfaces are minimally bored (0.5mm to 3 mm diameter). One each of *A. palmata* (3 cm long), *Diploria* sp. (1 cm long) and *M. annularis* (5 cm long).

CORE BJC#3



- Well-preserved *M. annularis, M.cavernosa, Homotrema*, some sponge borings
- *A. palmata* well preserved and bored
- -26.15 to -27.87m: Coral floatstone; dense, white skeletal grainstone matrix with *Homotrema*, gastropods, *Halimeda*, scattered broken bivalves (up to 2 cm long), benthic forams. Well-lithifed. Corals include *A. cervicornis* (1-3 cm diam.), *A. palmata, Diploria, M. annularis* to -28 m. Pieces 1-6 cm long. Serpulids present in borings.
- Increasing amounts of coral pieces interspersed with 1-3 cm thick skeletal grainstone layers (some with brown staining). Increasing *Halimeda*.
- Interval -27.85 to -28.0 m contains 4-5 cm diam. pieces of *M. annularis, Diploria* and one *Agaricia*.
- Well-preserved *M. annularis*. **PP-3-32**.
- **MC99-3-33.7**
- *Manicina areolata* piece 4 cm long. **MC99-3-35.5**
- *Halimeda* floatstone with *A. palmata* fragments up to 5 cm long.
- *Halimeda* float/rudstone with coral fragments. **MC99-3-39**
- **MC99-3-39.9**
- Skeletal packstone with slightly leached coral fragments (*M. annularis, A. palmata, A. cervicornis, Porites, Siderastrea*). Well-lithified. Partly leached *Halimeda* throughout.
- Skeletal grainstone with scattered coral and *Halimeda* plates.
- *Halimeda* floatstone alternating with *M. annularis*. *Halimeda* plates are white or leached out. Benthic forams, 0.5 - 1.5 cm long corals, bivalves also present.
- *Halimeda* floatstone. Borings present.

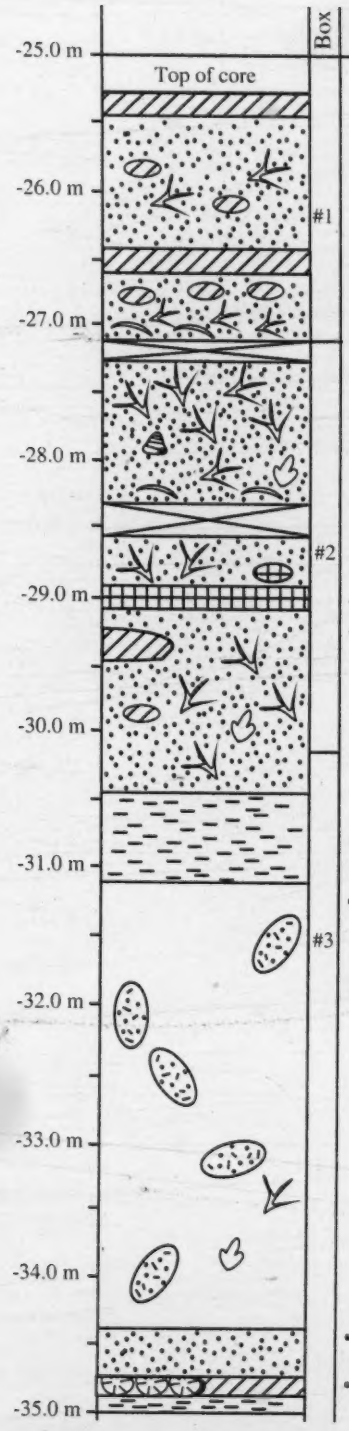
CORE BJC#3



Description

- *Halimeda* floatstone with coral fragments (*M. annularis, Diploria, A. cervicornis, A. palmata),* benthic forams, *Lithophaga*. Good preservation.
- *Halimeda* floatstone with plates leached out. Pieces of *M. annularis*, and bivalves. Rubbly.
- Skeletal packstone, well-lithified, with small bivalve and gastropod fragments, some *Halimeda*. Crumbly around -38.4 to -38.7m.
- Several borings (< 0.5 cm), abundant benthic forams.
- **PP-68.0**
- Skeletal packstone. ~20 % grains are leached out. Well-lithified with 2-6 cm *M. annularis* pieces, 2-8 cm *A. palmata* fragments, scattered leached *Halimeda*, numerous bivalves, some brown staining.

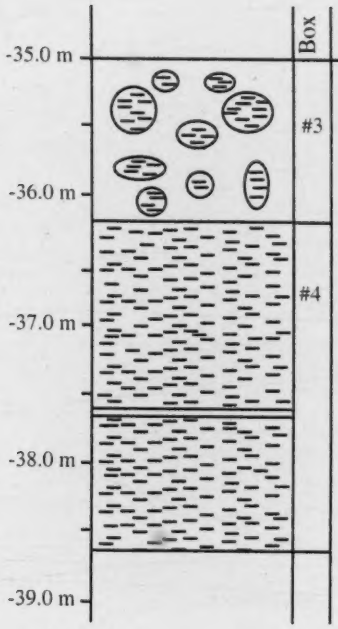
CORE BJC#4



Description

- *Montastrea annularis*. 3 cm diam. boring in top 14 cm. Filled with very fine sediment (encrusting red algae, shell fragments, unidentified skeletal grainstone). Lined with secondary calcareous serpulids and scattered *Homotrema*.
- Well-lithified, coarse sand. Scattered *M. annularis, A. cervicornis* (1-3 cm diameter). Mud patches (<1 cm across) amid very fine to fine skeletal pack/wackestone matrix.
- Well-preserved *M. annularis*.
- Well-lithified, *M. annularis* pieces (-26.7 to -26.9 m) with *Lithophaga* (?) borings; bivalves, *A. cervicornis, Manicina* sp. (-26.9 to -27.1 m). Poorly sorted skeletal grainstone matrix (very fine-coarse).
- Rock less lithified than overlying material (-27.3 to -28.3 m). *A. cervicornis* rudstone with poorly sorted skeletal grainstone matrix. Coral pieces have horizontal to 30^{o} orientation. One piece *Porites porites* (?) 3 cm diameter. Matrix grains very fine-coarse, subangular to subrounded (includes red algae, benthic forams, echinoid spines, unidentified grains). Coral concentrated in interval -27.3 to -27.6 m; decreasing to -28.2 m. Gastropods (up to 6 cm length) and bivalves from -28.0 to -28.3 m. Cavities present (-27.3 to -28.4 m). *Lithophaga* borings in *A. palmata*.
- Same facies and matrix as (-27.3 to -28.3 m).
- Single, well-preserved *Diploria labrinthyformis* head.
- Coral rudstone (*M. annularis, A. cervicornis, A. palmata*) with skeletal grainstone matrix (same as for interval -27.3 to -28.3 m).
- -30.1 to -30.4 m: Very lithified coral floatstone with medium to very coarse skeletal grainstone matrix. *A. cervicornis, A. palmata, M. annularis*, red algae, 1 cm long disarticulated bivalve shells. *Lithophaga* boring in coral filled with matrix. Mud patch with vertical 4 cm long, 0.5 cm wide burrow.
- -30.45 to -31.1 m: 50% recovery. Friable *Halimeda* float/rudstone with some shell fragments.
- -31.2 to -34.4m: Friable, powdery, very porous, very fine to fine grained pack/wackstone with shell fragments. 5% recovery. Some scattered corals--one Fe-stained *A. palmata* 4 cm long, several badly preserved *A. cervicornis* encrusted with red algae.
- -34.4 to -34.8 m: Porous *Halimeda* float/rudstone. *Halimeda* plates are completely leached. Patchy rusty staining at -34.7 m.
- *M. cavernosa* and *M. annularis*.

CORE BJC#4



Description

- 63% recovery over interval - 35.0 to -36.2 m. Highly porous *Halimeda* float/rudstone rubble with leached *Halimeda* plates.
- -36.2 to -38.6 m: *Halimeda* rudstone with floatstone patches. *Halimeda* are completely leached, leaving well-preserved, 1 cm long molds arranged horizontally or up to 30°. Scattered disarticulated bivalve shells (1-2 cm long), some fragmented, some with original colour. Minor very fine to medium skeletal grainstone matrix.
- Laminar form of *M. annularis*. Two 3 cm layers of coral 4 cm apart.